POTENTIAL OF PERENNIAL SORGHUM and RICE in SSA, South and South-east Asia

FINAL REPORT

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Future Farming Food Systems

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List of Acronyms and Abbreviations

AGD	Average Growing Days
APFS	Agropastoral Farming System
AR	Annual Rice
AS	Annual Sorghum
CASI	Conservation Agriculture Based Sustainable Intensification
CGIAR	*Consultative Group for International Agriculture Research*
CIMMYT	International Maize and Wheat Improvement Center
CRCMFS	Cereal Root Crop Mixed Farming System
ESCA	Eastern, Southern and Central Africa
FAO	Food and Agriculture Organization of the United Nations
FARA	Forum for Agriculture Research in Africa
FS	Farming System
IITA	International Institute for Tropical Agriculture
IRRI	International Rice Research Institute
LGP	Length of Growing Period
MAS	Market Assisted Selection
MMFS	Maize Mixed Farming System
MoA	Ministries of Agriculture
NARS	National Agricultural Research System
NARES	National Agriculture Research and Extension Systems
NGO	Non-governmental Organization
PS	Perennial Sorghum
PR	Perennial Rice
R&D	Research and Development
SIMLESA	Sustainable Intensification of Maize-Legume Systems for Food Security in Eastern and Southern Africa
SA	South Asia
SDG	Sustainable Development Goals
SEA	South-east Asia
SSA	sub-Saharan African
TLU	Total Livestock Unit
USAID	*United States Agency for International Development*
WCA	Western Central Africa

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Main Report

Annexes:

Executive Summary

Building on the presentations and discussions of the Perennials Grains Convening organized by BMGF and USAID during April 2022, this assessment analyzed the potential of perennial sorghum (PS) and perennial rice (PR) in sub-Saharan Africa (SSA), South Asia and South-east Asia. While PS will require at least a decade for the development of lines ready for widespread testing on farms, PR has been released in Yunnan China where it is grown by 45,000 farmers, and also released recently in Uganda. Tests in Senegal and Cote d'Ivoire have shown promising results as well. In each location PR has regrown from the original plants for three or four years without special management, while out-yielding well managed transplanted annual rice (AR). This assessment consulted with more than 75 well-informed R&D experts, the vast majority of whom favored perennial crop R&D and underscored the broad interest of many agricultural scientists and policy makers in perennial grains.

The assessment identified 5 major target farming systems to estimate the potential for PS adoption and impact in SSA and South Asia; and 13 target farming systems to assess the potential of PR in SSA, South Asia and South-East Asia. These farming systems will evolve substantially over the decades from 2022 to 2050 in response to climate change, market development and a spectrum of new technological and institutional innovations. In line with the 'Towards Sustainability' scenario of a recent FAO foresight study (FAO 2018) and through farmer adoption of new biological, mechanical, digital and institutional innovations, land and labor productivity is expected to increase substantially in SSA – but more emphasis is needed on farming systems resilience and sustainability.

The developments of PS and PR have the potential to fundamentally transform farming and agri-food systems by 2050. The integration of these perennial grains into the farming system represents a significant step towards climate resilient on-farm diversification. These multi-purpose perennial crops bring a wide set of benefits. The direct benefits include increased and relatively reliable food grain, increased family income, savings of labor and production costs in the second and successive years, extra forage for livestock (especially in the case of dual-purpose PS), increased farm system stability and resilience and environmental benefits in terms of the reduced soil erosion and increased soil organic carbon. The perennial grains do not just augment farm production but could transform the system — for instance, the savings of crop establishment labor during the second and subsequent years would enable timely planting and weeding of other crops, which often suffer yield penalties from late planting or weeding. One indirect benefit is the reduced risk of crop loss during crop establishment during seasons 2, 3, and 4. This will enable many smallholders to increase their judicious application of nutrients and herbicides, increasing productivity and reducing labor.

The nature of perennial grains lends themselves to small scale tests by farmers which enables farmer learning and fosters adoption. However, access to information, seed, finance and markets will depend on national scaling programs. The increased yields and savings of labor and production costs are three major drivers of adoption. This assessment assumes that scaling of PR in SSA will commence during the current decade, and for PS in the mid-2030s. Initially, farmers are expected to replace a portion of the AS or AR crops. However, as their confidence and experience grow and market demand expands, they are likely to replace some areas of other crops with PS and PR.

Most international development agencies expect considerable improvement in sector governance and policies by 2050 which, alongside expanded and diversified value chains and a wide range of new technological and institutional innovations, will create the conditions for faster adoption rates in the coming decades than seen during past decades. Assuming the release of PS cultivars in the mid-2030s and effective national scaling programs in key countries, it is plausible that by 2050 PS could be harvested from 4.2 m ha in SSA and a further 4.5 m ha in South Asia, likely reversing the trend of declining sorghum areas. Building on the existing releases the continuing improvement of cultivars, PR has the potential to be adopted on more than 26 m ha by 2050. Both perennial grains improve and stabilize food production, increase family income and improve soil health – and in the case of PS increase quality forage availability for livestock.

The full list of recommendations arising from this assessment are listed in section 4.3. Here we highlight a few salient recommendations in relation to (1) target farming systems (2) perennial sorghum development and (3) perennial rice development. In relation to target farming systems a high priority should be given to the development of PS and in due course its scaling using a risk management strategy for the semiarid Agropastoral FS in SSA. In this FS, severe climate change impacts the agricultural population of over 100 million of whom more than half are severely undernourished and poor. As the second priority, the combined subhumid Maize Mixed FS and Cereal Root Crop Mixed FS with more than 75 m ha of potentially productive cropland, sometimes called the ‘sleeping giant’ of SSA agricultural development, would benefit enormously from PS and PR adoption to augment system intensification and diversification. Farming systems crop and whole farm simulation modelling should be conducted to inform the management of climatic and market risk. Further analysis is required of the probable impact of climate change on SSA farming systems during future decades. Targeted investment in innovative scaling strategies involving smallholders, seed businesses and service providers, is recommended. In this connection, the social science research and monitoring will be critical.

In relation to the PS and PR crop improvement, the development of molecular screening tools such as MAS, especially targeting root-and- rhizome-linked traits, as well as physiologically complex traits such as drought and termite tolerance, should be continued. For PR, and especially for PS, the BMGF should adopt a “stop-go” approach to supporting investments in perennial crop research and scaling. For both perennial crops there are a range of abiotic, biotic and socio-economic challenges that merit strategic applied research. The associated systems considerations need to be addressed throughout, including the finetuning of agronomic practices and institutions in order that PS and PR can deliver transformative impacts. The perennial crops research should be linked to ongoing research on the annual crops. The BMGF should facilitate a higher-level partnership of development institutions, governments, private enterprise and civil society to map out strategy and policy toward scaling adoption and utilization of PS and PR in SSA.

From the full list of recommendations for PS development provided in section 4.3, we wish to highlight the following recommendations:

- The research program targets vegetative bud survival during the 8 months dry season of the Agropastoral FS including screening of sorghum germplasm and/or transfer rhizomatous trait from wide crosses, coupled with backcrossing to incorporate necessary agronomic and organoleptic traits.
- Wide crossing to “weedy” rhizomatous parents be processed with FAO protocols for managing potentially invasive species.
- Conducting studies on termite impacts on rhizomes and stem crown during long dry seasons to identify best-bet approaches.
- Consideration should be given also to development of perennial sweet sorghum, based on new breakthroughs at Texas A&M, and other and other transformative traits for PS in the Agropastoral FS.

From the full list of recommendations for PR development outlined in section 4.3, we wish to draw attention to the following critical recommendations:

- Current cultivars of PR should be promoted for adoption under relatively favorable conditions in SSA, South Asia and South-East Asia.
- Back-crossing PR to popular African cultivars such as Sahel-108 and WITA-9 and the introgression of the sub-1 trait should allow improved PR cultivars to be available by 2030 which would be adoptable in a wider range of humid farming system contexts.
- Longer-term PS crop improvement is needed to include traits for dry season survival, especially for long dry seasons exceeding 3 months in duration in some subhumid farming systems.

CHAPTER 1

Introduction

This report is focuses on the potential of perennial sorghum (PS) and perennial rice (PR) in sub-Saharan Africa (SSA) and South Asia (SA) and PR in South-East Asia (SEA). Over the past few decades Interest has been growing in the potential role of perennial grains to complement annual cereals in agrifood systems (Glover et al. 2010). The Gates Foundation examined the potential for perennial grains in a Convening during 2012, commissioned a follow-up study by Michigan State University on perennial grains for Africa and, in partnership with USAID, arranged a second Convening on Perennial Grains in April 2022 to appraise developments. There has been modest progress with the development of PS and substantial advances with the development of PR, including the release of three competitive PR lines in Yunnan Province China and one line in Uganda. In a recent review of the development of perennial food grains, Cassman and Connor (2022) attribute slow progress with many perennial grains to four missing dimentions: minimum grain yield targets for economic viability; designated target regions where perennial grains would be competitive against annuals; selection focused on yield per se rather than components of yield; and adequate R & D investment compared to ongoing investments for annual crop improvement.

This analysis-focuses on answering the following key questions: (1) where could PS and PR be adopted given the feasible sets of product profiles; and (2) what food security, farm income and environmental benefits could be generated by widespread adoption and scaling? Relatedly, has the business case for investment in R&D on PS or PR changed over the past decade. The primary focus is placed on SSA and secondary attention is given to SA and SEA

This Chapter sketches the stress and stagnation of farming and food systems in SSA and Asia. Section 1.2 identifies the farming systems with greatest potential for PS or PR over the coming decades to 2050. Section 1.3 considers the nature of perenniality for food grains. Section 1.4 outlines relevant aspects of adoption and scaling of perennial grains in the target farming systems. Chapters 2 and 3 set forth the principal findings in relation to PS and PR respectively, including potential performance, adoption and benefits in different farming systems. Chapter 4 discusses the implications of the findings in relation to the transformation of farming systems driven by climatic, technological and market change and considers the role of risk. Chapter 4 consolidates conclusions and recommendations. The Annexes contain supporting materials for the primary chapters, as well as references and primary contacts.

1.1 Food system stresses and stagnation in SSA and Asia

Food and economic security are critical challenges in the developing regions (Gates 2022), especially in rural SSA, SA and SEA which contain the greater part of global poverty and undernourishment. For instance, the undernourished population in Africa is estimated as 278 m in 2021 and projected as 311 m in the 2030 (FAO 2022a). Annual food grains such as sorghum (AS; 65 mmt globally), rice (AR; 510 mmt milled), wheat (778 mmt) and maize (1207 mmt) form the backbone of these region's food and feed supplies. However, the farming and food systems associated with these crops are under severe stress from soil degradation (FAO 2021), weak value chains and climate change (IPCC 2021) recently aggravated by geo-political turbulence (FAO 2022a).

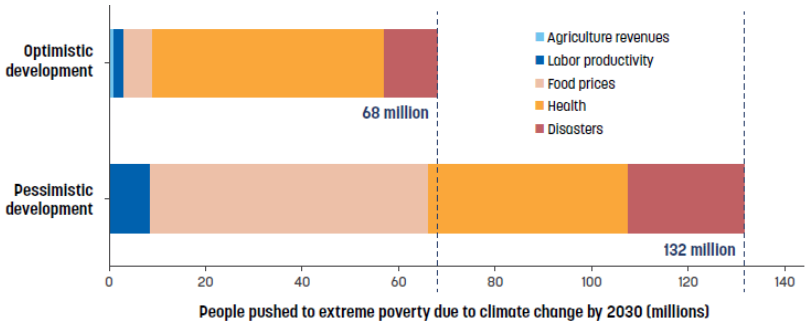


Figure 1.1. Populations pushed to extreme poverty by 2030 from climate change

As FAO (2022) noted, these systems are at breaking point and substantial areas of the cultivated lands of the three regions are at high risk. Frequent cultivation has led to high levels of soil erosion and degradation. Continuation of such practices in ecologies with fragile soils is resulting in serious deterioration of the natural resource base, namely, physically and biologically healthy soils able to absorb moisture and optimize plant nutrient uptake and cycling).

Because of their persistent vegetative cover and extensive roots that hold moisture and access soil nutrients, adoption of perennial crops may help reverse land degradation (well-articulated by Glover et al 2010). Perennial crops may also offer the potential to increase total seasonal productivity through greater total light interception during longer growing periods in Africa and Asia resulting in increased forage and grain yields and increased resilience. In theory, PS could be grown with less negative, or even positive impacts on soil health, and are more likely to provide stable yields in the face of climate change and increased variability (Cox et al. 2018). Similarly, PR offers not only equal or increased yields than annual rice but also reduced crop establishment labor and production costs and greater stability of farm incomes (Futakuchi et al. 2021). However, SSA and Asian agricultures are extremely heterogeneous, and PS and PR would fit best and be adopted faster in certain selected farming systems which favor PR and PR over annual sorghum or annual rice.

1.2 Main farming systems in SSA and Asian agriculture

Farming systems (FS) are defined by current livelihood patterns as shaped by agroecological characteristics and socioeconomic characteristics (Dixon et al. 2001). In 2000 the FAO, at the request of the World Bank, prepared a global classification of 72 major farming systems in six developing regions to guide the Bank's strategic investments in agricultural and rural development. Each of the farming systems is characterized by the central tendency of the core livelihood pattern of farm households, shaped primarily by the agroecological factors which underly potential biomass productivity and the access to agricultural services notably input and produce markets, which frame the range of viable livelihood options available to ~~the~~ households. The classification and mapping of farming systems zones informs research (for example the CGIAR Challenge Program designs), investment (for instance the update of the World Bank's 2001 Rural Development Strategy) and policy decision making.

The African farming systems analysis was subsequently updated and deepened for the SDG era (Dixon et al. 2020). Figure 1 shows the 15 broad farming systems of continental Africa, and Annex 1 contains a summary of core characteristics and data for each farming system. Most of the farming systems have defined sub-systems. All the farming systems contain mixes of crops, livestock and trees, and many households depend also on off-farm income.

As illustrated in Table 1, the extensive Agropastoral FS is found in east, west and southern Africa. As of 2015, the agricultural population of 98 million depended on 443 million ha of substantially degraded range and cropping land with an average of 130 growing days per year (LGP). The households cultivated 68 m ha of rainfed sorghum and millet and managed 72 million tropical livestock units (TLU) of cattle, sheep, goats and camels with low-medium market access especially for livestock sales. Resilience is low, and livelihoods are extremely vulnerable to climate change and climate variability. Household income is low and extreme poverty is prevalent. The Agropastoral FS has been divided into a number of subsystems depending on the agroecological and market/policy context (see Chapter 4, Dixon et al.2020). This pan-African classification is complemented by national farming systems studies in selected countries, for example Amede et al. (2015) for Ethiopia.

Considering the current or probable conditions for PS or PR (see section 1.3 on perennial grains, section 1.4 on adoption and ensuing Chapters) and the current and future characteristics of the farming systems, three farming systems were chosen for PS and by the team in consultation with experienced scientists. These three farming systems listed in the sidebar table contain 142 m ha of cropland and support an agricultural population of 248 million – as will be seen later, PS would only be adopted on a proportion of this area. The largest farming systems is the Agropastoral FS with an average of 130 days LGP annual sorghum as the major cultivated food grain – a transition between the medium potential maize/sorghum/cassava farming systems and the Pastoral FS dominated by livestock-based livelihoods. The drier margins of the Maize Mixed FS in ECSA and the Cereal Root Crop Mixed FS in WCA are also targets for PS. Where in the future, climate change mediated drying of marginal zones of maize belt occurs, sorghum production will likely increase. On the other hand, early maturing and drought tolerant maize has already replaced some sorghum lands in SSA land. Details appear in Chapter 2.

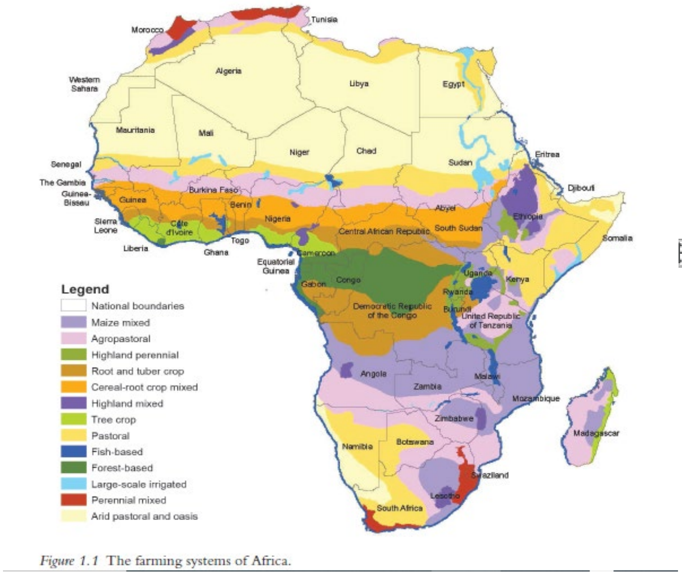
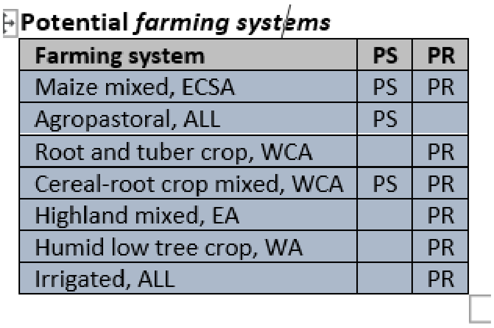


Figure 1.1 The farming systems of Africa.



Potential *farming systems*

Farming system	PS	PR
Maize mixed, ECSA	PS	PR
Agropastoral, ALL	PS	
Root and tuber crop, WCA		PR
Cereal-root crop mixed, WCA	PS	PR
Highland mixed, EA		PR
Humid low tree crop, WA		PR
Irrigated, ALL		PR

Figure 1.1. African farming systems map and potential farming systems for PS and PR

Six farming systems hold promise for PR (two are common with PS) with 130 m ha of cropland supporting an agricultural population of 323 million. Chapter 3 explains the prevalence of favorable irrigated, rainfed lowland and upland areas within each farming system. The Large-Scale Irrigated Farming system is a natural target for PR, as are the small-scale irrigated schemes (formal and informal) in the Maize Mixed and other medium potential FSs. The moist parts of the Maize Mixed FS and the Cereal Root Crop Mixed FS with around 200 days LGP are prime targets for PR, as is the humid Root Tuber Crop FS in WCA and the humid Lowland Tree Crop FS. Finally, PR could be adopted in niches of the Highland Mixed FS above 1700 masl.

Table 1.1. Potential system fit of perennial rice and perennial sorghum in major African farming systems (see Annex 1 for System fit tables for South Asian and South-East Asian)

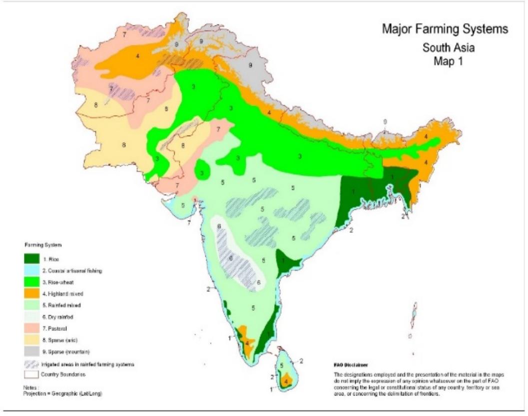
Farming system	**LGP (d)**	**Market access (L-M; hrs)**	**Cultivated land (mha)**	**Livestock (mtlu)**	**Agric. pop (m)**	**Key system characteristics**	**Potential system fit – PR**	**Potential system fit – PS**
Maize mixed	196	M 8.3	40 (irrig 1.9)	36	107	Mixed farming in subhumid areas incl SSI of East, Central and Southern Africa; legumes, cassava, tobacco, cotton, cattle,	**** (moist part,	**** (dry margin)

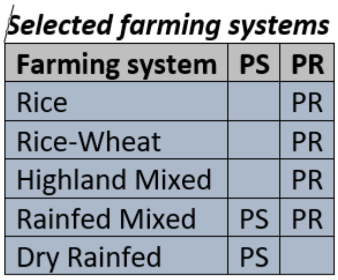
						shoats, poultry, off-farm work (Aver 2.1ha, 1.9tlu). <Includes SSI>	irrigated niches)	
Agropastoral	130	L-M 7.1	68 (Irrig 1.5)	72	98	Mixed crop-livestock farming in semiarid, often depending on wheat, barley and sheep. In SSA the main food crops are sorghum and millet and livestock are cattle, sheep and goats. In both cases, livelihoods include pulses, sesame, poultry, off-farm work (3.8ha, 4.0tlu).	X (irrigated niches)	*****
Root and tuber crop	269	L-M 8.8	23 (Irrig 0.15)	8	50	Lowland farming dominated by roots and tubers (yams, cassava) found in humid areas of West and Central Africa. Other livelihood sources include legumes, cereals, off-farm work (2.5ha, 0.9tlu).	***	X
Cereal-root crop mixed	187	M-H 7.3	34 (Irrig 0.2)	29	43	Mixed farming, at least two starchy staples (typically maize and sorghum) alongside roots and tubers (typically cassava), in the subhumid savannah zone in West and Central Africa. Also, legumes, cattle, off-farm work (4.3ha, 3.7tlu). <Includes Inland Valley Swamps>	*** (moist part)	**** (dry margin)
Highland mixed	183	L-M 7.1	13 (Irrig 0.2)	28	45	Highland mixed farming above 1700m. dominated by wheat and barley, in subhumid north-east Africa with pockets in Southern, West and North Africa. Also, teff, peas, lentils, broad beans, rape, potatoes, sheep, goats, cattle, poultry and off-farm work (1.6ha, 3.5tlu).	*** (irrigated niches)	**
Pastoral	64	L 8.3	33 (irrig 1.1)	42	38	Extensive pastoralism (dominated by cattle), found in dry semiarid. Also, livestock include camels, sheep and goats alongside sorghum, millet in moist areas, plus off-farm work (4.7ha, 6.0tlu).	X	X
Humid lowland tree crop	299	H 4.7	8 (irrig 0.1)	3	30	Lowland farming dominated by tree crops (> 25% cash income from cocoa, coffee, oil palm or rubber) found in humid areas of West and Central Africa. Also citrus, yams, cassava, maize, off-farm work (1.4ha, 0.6tlu).	****	X
Irrigated	54	M-H 3.8	12 (Irrig 10)	23	48	Large-scale irrigation schemes associated with large rivers across Africa, e.g., Nile, Volta. Often located in semiarid and arid areas Includes the associated surrounding rainfed lands. Diversified cropping includes	*****	***

						irrigated rice, cotton, wheat, faba, vegetables and berseem augmented by cattle, fish, poultry (1.3ha, 2.6tlu).		

Notes : Source Dixon et al (2020). Data benchmarked to 2015. LGP -- length (or number) of growing days in the year, including secondary or bimodal rainfall. Market access -- rated L low to H high indicated by travel time in hours to nearest major market center. System fit low * to very good ****.

In South Asia two farming systems would be leading targets form PS, viz, Rainfed Mixed and Dry Rainfed which currently contain the majority of annual sorghum production in South Asia. There are at least four promising farming systems for PR adoption, including the lowland (flood prone in parts) Rice FSs in coastal and delta lowland areas of Bangladesh and India, the irrigated Rice-Wheat FS food bowl of South Asia (including Punjab, UP, Bihar and Orissa), the Highland Mixed FS (including Nepal) for both irrigated and upland PR, and the Rainfed Mixed FS.



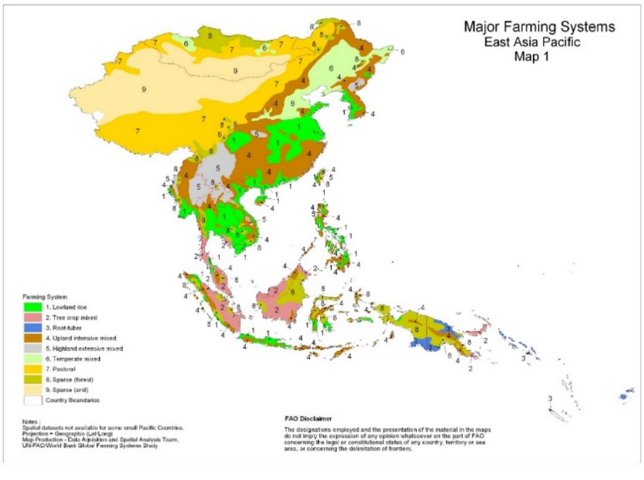


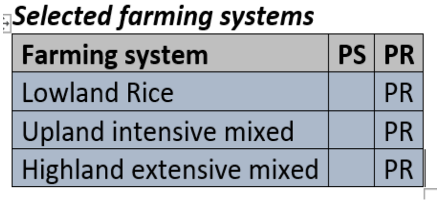
Selected farming systems

Farming system	PS	PR
Rice		PR
Rice-Wheat		PR
Highland Mixed		PR
Rainfed Mixed	PS	PR
Dry Rainfed	PS	

Figure 1.2. South Asian farming systems map and potential farming systems for PS and PR

South-East Asia has not been considered for PS (little sorghum is grown and markets are small), but PR could be adopted on parts of the Lowland Rice FS (especially deltas and inland irrigated plains) and in the Upland Intensive Mixed FS and to some degree in the Highland Extensive Mixed FSs – in the second and third farming system PR could be irrigated, rainfed lowland or upland.





Selected farming systems

Farming system	PS	PR
Lowland Rice		PR
Upland intensive mixed		PR
Highland extensive mixed		PR

Figure 1.3. South-East Asian farming systems map and potential farming systems for PS and PR

These farming systems may evolve substantially over future decades as a result of trends in seven major drivers: population, natural resources/climate, energy, information systems, technology, markets and policies. Total SSA population will increase massively, although rural and agricultural populations will increase and then gradually decline. To indicate the magnitude of the change, IFPRI (2019) projects that aggregate food production in SSA will increase in by 55% between 2010 and 2030, and by 110% by 2050. IFPRI (2019 provides a rich set of projections to 2050. FAO (2018) reports on the modelling of agriculture and food to 2050. Table 2 summarizes several key indicators (see Annex 1 for details).

Table 1.2. Projected trends in SSA to 2050

	2020	**2030**	**2040**	**2050**
Total population (m, Africa)	1363	1703	2100	2528
Rural population (m)	765	880	975	
Climate (IPCC)	Observed changes of temperatures and precipitation	Increased storm intensity	Increased precipitation in East African highlands	Drying in southern and western Africa
Aggregate food production (IFPRI 2019)	(2010 based)	+55% cf 2010	na	+110% cf 2010
Sorghum area (mha)	27	37	45	51
Sorghum yield (t/ha)	1.01	1.21	1.34	1.48
Rice area (mha)	17	25	29	31
Rice yield – irrigated (t/ha)	3.3	3.8	4.2	4.6
Rice yield – rainfed (t/ha)	1.9	2.2	2.5	2.7

Sources : Rural population UN. Climate change IPCC. Aggregate food production IFPRI (2019). Annual sorghum and rice area and yield projections FAO (2018), reporting the *Towards sustainability scenario,* based on the year 2012.

1.3 Perennial food grains

This section provides some further background on the nature of perennial food grains. For decades the potential of perennial grain crops has been advocated as sustainable alternatives to an agriculture dominated by annual grain crops (Glover et al 2010). Proponents emphasize the potential of perennial grains to mimic natural systems and thereby reduce soil erosion, nutrient losses, and degradation of soil quality. Annual grain crops were first domesticated in the Neolithic period (Scott, 2017), with their annual habit conferring a greater sink priority to grain formation, in the absence of a need to invest in regrowth capacity (axillary buds, tillers, stolons, rhizomes, roots) for the next cycle (Loomis and Connor, 1992). Their higher grain yield and input efficiency relative to traditional landraces ensured their dominance under cultivation, but also ensured ground cover was intermittent, which was associated with losses of soil, nutrients and soil organic carbon (SOC), thereby compromising ecosystem services (Crews et al., 2018).

Wide hybridization between related annual and perennial species commenced in Russia in the 1920s (Tsitsin and Lubimova, 1959; Wagoner, 1990), but early efforts lacked floret fertility and had undesirable agronomic traits. Successful hybrids were later reported in rice (Tao and Sripichitt, 2000; Sacks et al., 2003, 2006; Hu et al., 2003, 2011) and other crops (Cox et al., 2006, 2010), with capacity to both regrow and set seed providing the opportunity to commence selection. Meaningful progress has now been made in perennial sorghum (PS) (Cox et al., 2018) and especially in perennial rice (PR) (Zhang S.L. et al., 2017, 2019, 2022 in review; Huang et al., 2018; Samson et al., 2018; Zhang Y.J. et al., 2021). Three PR cultivars have been released in Yunnan Province, China (PR23, PR25, PR107) and one in Uganda (PR107).

Perennial crops with deeper roots could increase nitrogen retention and SOC accumulation, improve labor efficiency and system flexibility by contributing both grain and forage for livestock, while retaining soil cover and reducing nutrient and soil loss, thereby maintaining ecosystem functions (Culman et al., 2013; Jungers et al., 2019). Nevertheless, perennial grain crops could pose additional challenges, such as nutrient immobilization with larger below-ground dry matter, control of weeds in undisturbed ratoon stands in the absence of cultivation, greater pest or disease incidence with continued infection in regrowth cycles or from previous stubble, and difficulty in removal after several cycles, in order to rotate to another crop or pasture. These potential constraints to perennial grains are examined in ensuing chapter, together with the strategies available to reduce their risks (Zhang S.L. et al. (2022, under review)).

The physiology of perenniality is complex and the details are beyond the scope of this report. Many, if not most, monocot plants including Sorghum and Rice are biologically perennial, if growing conditions continue to be favorable after seed set. Access to water is the key determinate for functional perenniality in Sorghum and Rice. *Sorghum bicolor* is considered botanically perennial, but in the semi-arid biome of SSA it is generally unable to withstand the long dry seasons. Rhizome-enabled survival and plant shoot regeneration following a long dry season, is considered the key to development of PS for the major sorghum zones.

1.4 Adoption, scaling and benefits

Adoption at scale requires many years or decades. In the later stages of the Green Revolution the mega cultivars developed by IRRI such as IR36 and IR64 were each adopted over about 10 mha during the course of 20 years (Mackill et al., 2018) which amounts to an adoption rate of approximately 0.6% per year of the global rice area of the time. The adoption rates of improved cultivars of rainfed crops, including PS, are typically slower than for irrigated crops, even for exceptional materials such as drought tolerant maize in SSA or some cash crops.

There is an extensive literature on the farm household characteristics and innovation characteristics which determine the rate and extent of adoption of improved cultivars such as PR or PS. A useful framework for qualitative estimates of adoption rates is offered with the smallholder ADOPT tool which can estimate the lag time to full adoption and the percent of adopters for well-defined technologies in well characterized populations (Kuenhe et al. 2017). The framework comprises four quadrants as the intersections of Population (i.e., target farming system) and Innovation (i.e., PR or PS) characteristics and Learnability and Relative advantage, as follows:

Table 1.3. Adoption framework

	Learnability	**Relative advantage**
Population, e.g., target farming system	Target farming system influences on learning about PR or PS	Relative advantage for the target farming system
Innovation, e.g., PR, PS	Learnability of PR or PS	Relative advantage of PR or PS (see product profiles and adoption drivers table for each target farming system)

The fastest adoption decisions are generally associated with decisions of “replacing like with like”, e.g., a new fertilizer blend for a currently used older fertilizer, or a new improved cultivar for a currently planted improved cultivar. In this assessment the relative speed of adoption and breadth of scaling depends on:

- Replacement of a portion of the annual rice or sorghum with PR or PS
- Expansion of cultivated area using PR or PS (sorghum is often considered a good pioneer crop)
- Replacement of different crop species with PR or PS

Both PS and PR potentially generate benefits in four areas:

- Extra grain (and forage in the case of PS) productivity, directly leading to improved household food security and farm income. In the case of PS, the additional quality forage could increase livestock weight and turnoff and thus increase total farm productivity and income
- Reduced labor input (especially women and in the case of PR, children as well) and reduced/eliminated establishment costs in second and subsequent years. The release of labor from PS or PR in second and subsequent years could be allocated toother rainfed crops to improve timeliness of planting which is a major existing constraint.
- Improved soil health such as reduced soil erosion in the case of PS, and improved soil organic carbon in the case of PR.
- Increased resilience of the whole farm through greater tolerance to drought, in part because of the expected deeper rooting

These benefits underpin the major drivers of adoption for each of the three pathways of adoption.

The increased resilience can be framed as states-of-nature (often 5 or 7) as shown in Table 1.4. The probabilities are purely illustrative. On-farm research results and crop modelling are useful for quantifying the impacts of productivity. Implications for permanence are not well understood at this stage of development of perennial grains. The implications for the farming system are a core consideration, directly affecting food security, farm income, soil resources and also system resilience.

Table 1.4. States of nature framework for risk assessment

State of precipitation	Proba-bility	Implications for PS or PR productivity and permanence	Implications for farming system
Exceptionally wet	e.g., 10%	Risk of waterlogging and crop failure for PS, and possible need for re-establishment	More likely in high potential farming systems than the Agropastoral FS
Above average amount and pattern of precipitation	e.g., 20%	Good yields for PS and PR, and also for annual crops.	Modest implications. Limited value of PS forage because of plentiful grazing resources. Annual crops yield relatively well.
Average amount and pattern of precipitation	e.g., 35%	None	None
Below average amount and pattern of precipitation	e.g., 20%	Relative advantage for PS and likely for PR over annual crops	PS and PR add to system stability including farm income and offer prospect of benefiting higher market prices during foodgrain shortages
Exceptionally dry and/or poor pattern of precipitation	e.g., 15%	Threat to permanence of PS during long severe dry, and risk of	Additional drought forage from PS for livestock.

Farmers' perception of the increased or decreased riskiness of PS or PR is a critical determinant of the relative advantage of the perennial trait (see bottom right quadrant of Table 1.3). Four benefits of perennial grain cultivars were listed earlier. The recent analysis of African farming systems explored the relative importance of five farm household strategies for escaping poverty and increasing income in each farming system, viz, intensification of existing farming patterns, diversification (i.e., introduction of new crops or livestock, growth of the farm business, increase of off-farm income and exit from agriculture. For these purposes, the replacement of an annual sorghum field with PS would be considered a form of intensification; but the replacement of millet with PS or the introduction of PS to a farm not growing sorghum would be considered diversification. The different strategies, e.g., intensification compared with diversification, have important implications for farm management and agricultural support services including market channels. The relative importance of various household strategies varies with the farming system, and Table 1.5 illustrates the average household livelihood strategies for Maize Mixed FS from 2015 to 2030.

Table 1.5. Perennial grains and livelihood strategies in Maize Mixed FS for the period 2015-2030

Strategy	**Average relative importance (of 10)**	**Implications of adoption of PS and PR for farming system**
Intensification	2.5	Both PS and PR adoption represents intensification with increased labor productivity. Freed labor can be deployed to improved timeliness of planting and weeding other crops.
Diversification	3.5	Freed labor and financial resources can be used for introduction of labor-intensive high value crops, e.g., vegetables, dairy, etc. Increased system resilience allows the introduction of riskier crops or livestock
Expanded farm business size	1.0	Both freed labor and financial resources can be devoted to larger herds or expanded cultivation where land and tenure permits
Increased off-farm income	2.0	Labor saving frees labor for off-farm employment
Exit from the farming system or agriculture	1.0	n/a

These livelihood strategies can be expected to change in future decades as the impacts of climate intensify, markets and institutional environments improve and farmer capital, management and education improve. For example, if farmers are successful with intensification during the current decade, delivering increased productivity and reduced yield gaps while foodgrain prices remain modest, farmers with options might give increased attention to diversification to higher value crops and livestock to boost household income. This discussion is elaborated in Annex 1.

These aspects will be developed further in the ensuing Chapters 2 and 3 which present the main findings for PS and PR respectively, and in the conclusions and recommendations in Chapter 4.

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CHAPTER 2

Perennial Sorghum

This chapter focuses on the status, potential and probable challenges of developing perennial sorghum (PS) for sub-Saharan Africa (SSA) and to a lesser degree South Asia (SA).

2.1. Needs, Status and Opportunities

For centuries annual sorghum (AS) has played a key food security role as a hardy, drought-tolerant staple crop in semi-arid areas of SSA and South Asia, for centuries. Grain is used as food, feed and in some parts for brewing beer. Forage is important ruminant fodder and stalks are used as roofing material and woven into mats. The agricultural populations of the sorghum-based farming systems are amongst the poorest in the world. Their large livestock populations have poor nutrition and low productivity.

Over the past two decades the AS harvested area in SSA has expanded by about 1% per year from 21.2 mha to 27.3 mha (compared with expansion of maize area from 24.2 mha to 43.1 mha). In contrast, in the densely-populated South Asia the AS harvested area has approximately halved from 10.2 mha to 5.6 mha during the same period. The crop is not grown widely in South-East Asia.

In SSA and South Asia AS is grown in mixed crop-livestock farming systems. In SSA, grain yield only averages about 1 t/ha. Expanding opportunities exist for AS in SSA and, in time, PS may be part of that future. Modest breeding efforts on PS have already led to “cautiously-encouraging” early results in the USA and West Africa (Cox et al. 2017). For SSA a main challenge for PS is vegetative survival across the dry season which can be up to 8-months long in the Agropastoral FS.

Both SSA and SA suffer from extensive soil degradation, primarily from soil nutrient depletion and water-driven erosion across exposed sloping lands (FAO 2021a). Climate change is leading to reduced precipitation in many semi-arid areas of SSA, coupled with high and escalating intra- and inter-seasonal variability and increased intensity of storm rain and severity of other extreme events (IPCC— https://www.ipcc.ch/report/ar6/wg2/). While there is modest expected decline in total rainfall many farming systems zones, many models suggest greater reduction in rainfall in the drier margins, especially in the Agropastoral FS during the next 30 years (Nidumolu et al., 2022). In addition, it is likely that the drier margins of the Maize Mixed FS and Cereal Root Crop Mixed FS may also experience reduced precipitation, in which case, some of the current maize could be replaced with the more drought tolerant AS or potentially PS.

Human populations in Africa are rapidly expanding, driving poverty and food insecurity sharply upwards (FAO 2018). Despite rapid urbanization, rural populations, many of whom suffer from severe poverty, increase slowly to 2040 and then begin to slowly decline. There has been slow growth in local and national demand for grain sorghum in SSA, but future demand as feedstock is expected to expand as livestock, poultry and fisheries production intensifies over the coming decades. With ruminant industries developing, the value of forages is also expected to increase. As well, markets for beverages and industrial uses are likely to grow. PS may well be part of the solution and opportunity, especially because risks of crop loss and input inefficiency will be reduced. Were only 2% of the current sorghum- and maize-based farming systems in SSA to be converted to PS, this would constitute more than a million hectares. At a modest grain yield increase of 1 to 2 t/ha, this would represent significant improved food security and livelihoods for millions – and in addition PS is likely to reduce greenhouse gas emissions and soil erosion. Consequently, the integration of PS into these farming systems may well stimulate the adoption of sustainable intensification practices for the whole farm.

2.1.1. Needs, food, income and risk

More than 100 million severely poor agricultural women, men and children depend in part on the leading sorghum-growing farming system in SSA, the Agropastoral FS, which extends across 445 million ha of range and cultivated lands. Climate change models foresee shift in the boundaries of the Agropastoral FS (a crop-livestock system): a substantial lower rainfall part of the zone could be converted to the Pastoral FS (dominated by livestock grazing) by 2050 (Nidumolu, 2022). However, at the same time, as rainfall amounts decline and patterns shift, the Agropastoral FS might gain land from the higher potential farming systems in some areas.

Farm income in the Agropastoral FS is derived from livestock sales supplemented by off-farm income and, in good seasons, from surplus food grain production. However, droughts and other climatic volatility, which are expected to intensify from future climate change (IPCC 2020, IPCC 2022, Nidumolu 2022), are major sources of risk for household livelihoods.

Because of decades of overgrazing and ploughing, much of the semi-arid Agropastoral lands in SSA are severely degraded, both in terms of soil structure and nutrients. Rainfall permeation and soil moisture holding capacity are badly compromised by loss of good soil structure and soil organic matter. This is aggravated by widespread soil erosion from intense storm rains, especially degrading of exposed soils at the start of the rainy season. Thus, there is a pressing need for restorative or regenerative farming practices, which simultaneously boost and stabilize productivity and improve soil health. There is also critical need for farming practices that increase and stabilize farm incomes from multiple sources. The need is also similar in sorghum growing areas in the drier margins of the Cereal Root Crop Mixed FS of WCA and of the Maize Mixed FS in ECSA. In coming years, climate change is expected to increase the frequency of dry seasons in maize zones. Sorghum, including PS, is the likely replacement for maize in ecologies no longer suited to maize. The need for frequent land preparation will be reduced through the adoption of PS, and PS will lend itself to conservation farming approaches with reduced soil disturbance in crop establishment.

With growing populations and incomes in future decades the demand for red meat and milk is projected to increase (Komarek et al., 2021). Thus, markets for feed grains (for mono-gastrics and increasingly for ruminants) and forages will expand. Sorghum forage markets are well developed in India and, remarkably, sorghum farmers often receive forage income which approaches the value of the grain crop. In the SSA Agropastoral FS, local forage markets are developing too, in part for fattening goats for sale to South African and Middle East markets. Forage markets are developing in other parts of the Agropastoral FS. Thus, future PS cultivars, capable of producing at least one fodder cut, or grazing, while still producing satisfactory grain yields, will be of great value in SSA's Agropastoral FS.

One compelling advantage of PS is the avoidance of risky crop establishment in the second and subsequent seasons of PS. There will be reduction in labor and costs of crop establishment at the onset of rains, at the time when there is great demand for time and financial resources for farm families in Agropastoral FS. The same is true for families in drier subzones of the Maize Mixed FS and the Cereal Root Crop Mixed FS. Resources used to plow or rip-line-plant AS and PS could be allocated to AS, cotton, green corn, okra, cowpeas, etc. Another advantage of PS would be efficient use of inputs and natural resources (sunlight and rainfall). PS is expected to have a deeper, more robust root systems than AS, and thus be better able to withstand dry spells during grain fill, ensuring food security in erratic rainfall years. The reduction of risks will likely enable farmers to invest more on inputs, especially crop nutrients. Even though a PS capable of long (6-8months) dry-season survival does not yet exist, there are a few locations in short dry-season zones (3 to 4 months) where farmers choose to ratoon sorghum (re-growing from crown buds). Socio-economic studies of these farmers could be revealing.

However, currently maize is the preferred cereal crop in short dry season medium to high potential zones in SSA, grown in mixed crop-livestock systems with numerous other food and cash crops (maize itself rarely represents more than 40% of the cropped area). Cassava, sweet potato and other root crops will continue to compete well with sorghum in bimodal rainfall and short dry-season zones. Nevertheless, sorghum remains a crop option of choice in sandy and low-fertility unfavorable niches in the current maize-based farming systems. The primary focus for sorghum adoption in the next decade, or maybe more, is expected to be in the drier farming systems. As mentioned above, where climate change makes maize too risky (foreseen by 2040 and beyond in some subzones—IPCC 2022), sorghum, including PS, will likely be a partial replacement. The feed market is also expected to be even stronger by then and that market too will be an increasingly strong driver for sorghum production growth.

With expected climate change-driven effects (shorter LGPs), it is probably by 2040 that the current Agropastoral FS zone will incorporate parts of the drier subzones of the current Maize Mixed FS and of the Cereal Root Crop Mixed FS of today. As noted above, drier parts of the current Agropastoral FS will likely become Pastoral FS due to lack of adequate reliable rainfall. By 2040, some Maize area will likely relocate into the currently wetter savannas as these zones on the forest margins dry.

2.1.2. Status and prospective product profiles of PS

Grain sorghum as a crop has been annualized over the last 6 thousand years as a food and feed grain crop. Sorghum was traditionally grown, including as a perennial food grain crop in short dry-season ecologies by many African farmers and still is, by some (Snapp et al. 2019). Sorghum cultivation preceded maize production in SSA by at least a thousand years. Today however, in conditions where maize can be grown reliably, many smallholders in SSA will give maize priority over sorghum – even though AS continues to be cultivated in the maize-based farming systems.

The origin and early domestication of sorghum is hypothesized to have taken place in northeastern Africa or at the Egyptian–Sudanese border around 5000–8000 years ago (Mann et al., 1983). The largest diversity of cultivated and wild sorghum is observed in this part of Africa. From the site of early domestication, sorghum later spread to other parts of Africa and eventually to Asia, including India, the Middle East, and China (Doggett 1970). Source: Rakshit. et al., 2016

Sorghum is, and will likely continue to be, primarily produced in agroecologies where maize cannot be reliably grown due to insufficient soil moisture or heat stress. One critical trait for PS, therefore, is long dry season survival. Survival is based on vegetative material (stem buds or rhizome buds) dormancy over the long dry season. Buds must survive termite damage over the dry season, and then reliably establish an adequate plant stand on the onset of new rains. The Consultancy Team has not found evidence that the huge *S. bicolor* germplasm collection was ever carefully evaluated for long dry season survival. **It is not probable, but not impossible, that stem crown buds of selected germplasm will go dormant and survive such long periods.** Smallholders in Uganda and Kenya are already able to ratoon (regrow) sorghum after 3 to 4 months' dry season, which is adequate for perennialism in areas having bimodal rainfall patterns and/or short dry seasons. It is possible that crown buds having the "stay green trait" and anti-metabolic levels of tannins will survive termite attack during the dry season. In the Conclusions and Recommendations Section of this report—Chapter 4 — we address this possible opportunity, suggesting targeted research that, frankly, should have been done in the 70s and 80[1]s.

One central vision of PS use in the "sorghum zones" of SSA is at least one fodder cutting during the rainy season and then a grain crop harvested at the same time as AS harvests after the rains. This would ensure grain quality and minimize bird damage which would be spread across all sorghum sown in the region. This could be achieved by continuing to use the short-day photoperiodism of traditional sorghum such that plants stay vegetative until grain will mature after the end of the rainy season. There is preliminary evidence (Rooney, 2022, pers comm) that genes for a "long juvenile trait" exist in sorghum, as they do in tropical soybean (Carpentieri-Pípolo et al, 2002) so that tropical sorghum varieties could flower timely across a range of tropical latitudes—short day conditions.

Cox et al (2004 & 2006), Rogé et al (2017), Glover (2005) and others have articulated the case for investing in PS development, including the proposition to explore transferring the rhizomatous trait for "overwintering" from related Sorghum species such as *S. halepense* or *S. Propinquum*. However, as will be discussed in the next section, not all reviews of the perennial concept are favorable (Loomis, 2022).

Interspecific crosses have been made at The Lands Institute in Kansas, and a few diploid progenies from the *bicolor x halepense* hybridizations were recovered. Modest rhizomatous expression was observed (Cox 2022, pers comm); however, the phenotypes of progeny did not have agronomic merit (they were more like Johnsongrass than cultivated sorghum) and the photoperiodic expression did not meet the needs for tropical sorghum. They flowered very early under short days in Uganda. Backcrossing is underway at the Lands Institute. Obtaining diploid perennials with good agronomic traits will likely take 10 years, or more, of focused breeding. This is likely worth the effort.

In an earlier study, some tetraploid (*bicolor x halepense*) recombinant inbred lines (RILs) showed promising survival of rhizomes across the long dry season in Mali, giving hope that this approach of wide crosses might, in time, result in desirable perennials for traditional sorghum zones in SSA (Cox, Weltzien, and Nebie, 2022, pers comms).

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[1] Resources for sorghum research in Africa were limited. Further, perennialism in the 80s was not considered a priority.

2.1.2.1. Relevant genetics and productivity

Development of rhizomatous-PS is still in early stages, as indicated above. In this section we note key selected elements of sorghum improvement and genetic control mechanisms[2]—to the degree currently understood—as they determine the merit, feasibility, and timely realization of rhizomatous -PS to meet the needs of selected smallholder farming systems. See figure 2.1 for examples of needed traits[3].

Length of growing season and crop duration are important parameters for varietal choice. Recording the days for 50% blooming in the genotypes is standard practice. The genotypes that take less time for flowering when planted late (moving into shorter days) can be considered photoperiod sensitive. In sorghum improvement programs in West Africa and post-rainy sorghum improvement in India, photoperiod sensitivity is a key trait. Were the long juvenile trait to be used to stabilize days to flowering over a range of short-day conditions, such lines would not change time to flowering when sown later under short days—behaving more like daylength insensitive, but would not flower under long days of temperate ecologies.

S. bicolor is genetically a perennial. It tillers from the crown buds and, if moisture and other growing conditions are favorable after seed maturation, it will regrow and produce a ratoon crop of both fodder and grain. S. bicolor does apparently not have enough energy and water reserves in the stem crown to keep the dormant buds viable for more than about 5 months of dry season. As stated above, the major challenge to create a plant type similar of Sorghum bicolor capable of long (6 to 8 months) dry season survival.

Dr. Baloua Nebie has kindly provided a proposed breeding scheme (see Figure 2.1.) for PSs in SSA based on incorporation of a rhizomatous trait from *S. halepense*. Such materials selected under long dry seasons will fit in the traditional sorghum zone, that is: the drier parts of the Maize Mixed FS, and the Cereal Root Crops FS, as well as the wetter subzones of the Agropastoral FS. The basic traits needed besides survival of long dry season are shown in the Table 2.1. below.

Table 2.1. Examples of important traits in addition to long dry-season survival (6 to 8 months for the Agropastoral FS and 5 to 7 months in the two primary Maize-based FSs)

Grain quality	Stover quality	Shattering resistance	Grain pest tolerance
Striga resistance	Resistance to fungal pathogens	Resistance to main viruses	Resistance to bacterial pathogens

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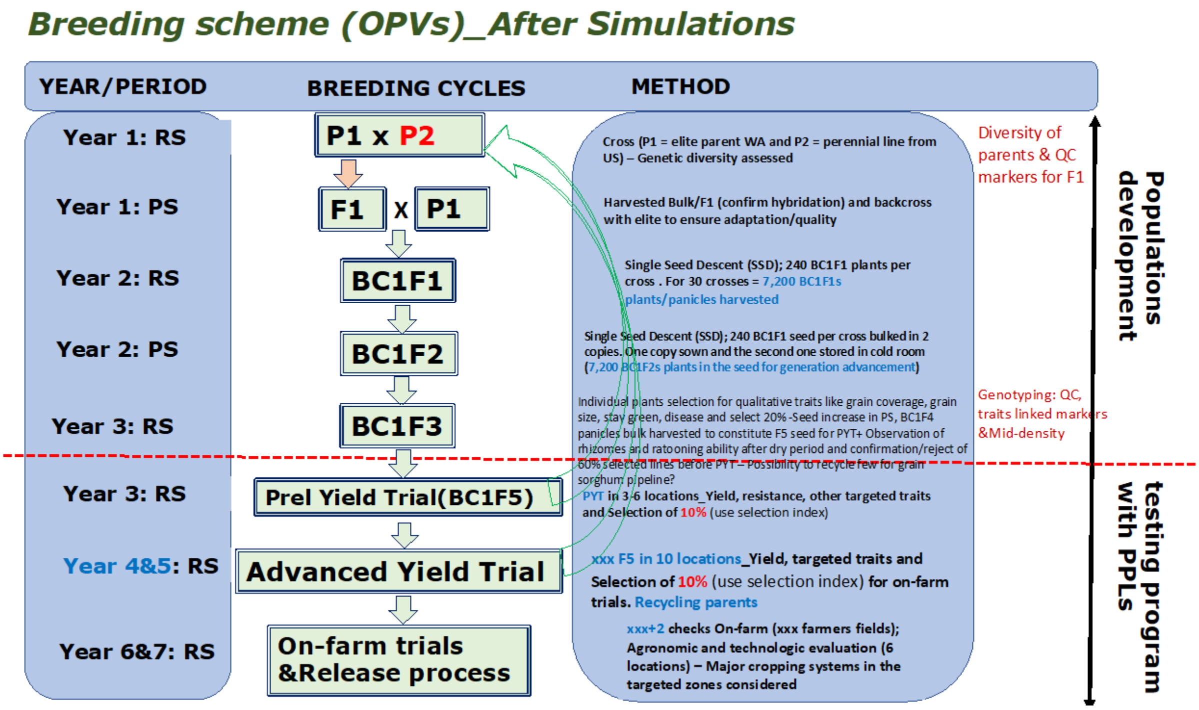
[2] A very useful compendium book was published in 2016 which is a major source of background for this section (The Sorghum Genome edited by S. Rakshit and Y. Wang. Springer. ISSN 2199-4781 Compendium of Plant Genomes ISBN 978-3-319-47787-9 DOI: 10.1007/978-3-319-47789-3

[3] Annex 2 provides some additional background information on sorghum improvement.

Panicle architecture	Drought tolerance	Resistance to leaf-feeding insects	Correct photoperiod adaptability[4]
Grain productivity	N.U.E., especially for nitrogen	Productivity for forage	Grain feeding insects resistance
Stem sugar content for bioenergy PS	Inclusion of long juvenile period trait for wide adaptation	Lodging resistance	Termite tolerance in dry season, including “Stay Green”



Cross (P1 = elite parent WA and P2 = perennial line from US) – Genetic diversity assessed

Harvested Bulk/F1 (confirm hybridation) and backcross with elite to ensure adaptation/quality

Single Seed Descent (SSD); 240 BC1F1 plants per cross . For 30 crosses = 7,200 BC1F1s plants/panicles harvested

Single Seed Descent (SSD); 240 BC1F1 seed per cross bulked in 2 copies. One copy sown and the second one stored in cold room (7,200 BC1F2s plants in the seed for generation advancement)

Individual plants selection for qualitative traits like grain coverage, grain size, stay green, disease and select 20% -Seed increase in PS, BC1F4 panicles bulk harvested to constitute F5 seed for PYT+ Observation of rhizomes and ratooning ability after dry period and confirmation/reject of 60% selected lines before PYT – Possibility to recycle few for grain sorghum pipeline?

PYT in 3-6 locations_Yield, resistance, other targeted traits and Selection of 10% (use selection index)

xxx F5 in 10 locations_Yield, targeted traits and Selection of 10% (use selection index) for on-farm trials. Recycling parents

xxx+2 checks On-farm (xxx farmers fields); Agronomic and technologic evaluation (6 locations) – Major cropping systems in the targeted zones considered

Figure 2.1. Proposed breeding scheme to incorporate **rhizomatous** traits of diploid parental lines from work of The Land Institute (TLI) and University of Georgia into well adapted West African Varieties with useful traits such as Striga resistance, disease resistance, and good plant morphology for productivity and mitigation of bird damage (Nebie pers. comm.)

While the figure 2.2. suggests on-farm trials could begin after 7 years, it is more probable additional cycles of crossing and selection will be required. The estimated time for a well-adapted PS cultivar could be as long as 12 years and even possibly more. Seed multiplication and demonstrations will probably require an additional 4+ years, recalling that the agronomic merit of the perennial habit needs to be tested over several years (3 or more). Farmers are unlikely to adopt PS based on one or even two seasons performance.

The choice of sowing a “non-invasive” rhizomatous -PS will expand options for livestock feed diversification—both as feed grain and fodder. In sorghum zones, rainfall is generally less than 750 mm and monomodal, with length of growing season less than 130 days in many areas. As rainy seasons are becoming increasingly erratic, there is a tendency toward early to medium maturity cultivars—less than 120 days to harvest. In theory, future developed rhizomatous-PS could replace substantial areas currently sown to AS and millet. However, currently there is no commercial rhizomatous-PS with long dry-season survival, although some progress in development is being made (Cox, et al, 2017; Rogé, et al., 2017 and P. Nabukalu 2022 pers comm.).

2.1.2.2. Product Profiles —varietal development goals for P-Sorghum

This section assumes that it is feasible and worthwhile to develop rhizomatous-PS without creating a pernicious weed like Johnsongrass. So, in brief, what would such an elite breeding line (or launched variety) look like?

Initially, the priority should focus on the dual purpose rhizomatous-PS that is high-yielding, produces good quality bold grain, and produces good quality leaf/stem fodder (probably with inclusion of the "stay-green" and brown-mid-rib genes, especially expressed in the early part of the 2nd season, so it can be ratooned at least once for fodder or grazed. Farmers will then let it grow to produce a grain crop in the rest of the rainy season. Stay green trait keeps leaf and stem feed quality high, and probably plays a role in reducing termite damage. In Nigeria and Niger, resistance to stem borer *Busseola fusca*, is a priority for NARS and ICRISAT. Stem borer resistance in PS will need to be included for such environments.

Plant height at maturity should be between 150 and 170cm. The line would need to be photoperiod sensitive so grain would not mature during the rainy season. Having the long juvenile period genes will give it wide adaptation to shortening days. The line will need about 75% re-establishment after 7 to 8 months of dry season. For this, rhizomatous ground-stems will likely be essential. It will need to be resistant or tolerant to the major races of striga, head smut, and anthracnose. The panicle type needs to be semi-open so birds cannot easily light-down for a full-course meal. The first lines should be of medium maturity and medium height so both grain and leaf/stem uses are met.

Farmers will need to perceive lower risks and lower crop establishment costs before wide adoption would be realized. Consequently, demonstrations on farmers' fields will be more challenging. Otherwise, grain yields will need to be at least 15% higher than current AS varieties on the most successful farmers' fields with their management. The lines should perform to this level over three rainy seasons. Weed management should be less demanding, as the shoots from rhizomes should emerge early and establish ground cover more rapidly than seedling shoots. This too will need to be demonstrated. The perennial crop should not accumulate pests and diseases and become a reservoir of such pests and diseases.

2.1.2.3 Agronomy and development adjuncts

There are a wide range of critical and desirable research topics that should either be ongoing, along with initiation of new perennial breeding efforts, or soon after rhizomatous diploid sorghum germplasm is available. Examples of the types of research that merit consideration are provided in the list of companion research areas below. For those topics selected for immediate action, a workshop involving national and international experts should be organized to develop action workplans with budgets for consideration by the donor community.

Companion research areas to support impactful applications of rhizomatous-PS:

- Studies on rhizome survival across lengths of dry season (GxE)
- Studies on weediness of P-Sorghum
- Studies on Striga build-up in P-Sorghum system with and without Striga-resistance genes
- Studies on termite damage to rhizomes
- Studies on weed management for perennial systems
- Studies on disease and pest management for perennial systems
- Studies on panicle structure and bird damage control
- Determine end-user desired traits, for example if brewers are OK with high tannin content
- Studies on tannin location and quantity on bird damage mitigation
- Studies on use of AFLASAFE for reduction in aflatoxins in grains
- Studies on catch-crop intercropping: early vegetables, extra-early Cowpea, Mungbean, fertilized green Maize, Sesame etc.
- Studies of P-Sorghum as understory in established *Faidherbia albida*
- Determination of extension needs which likely need to include farmer learning/discovery approaches.
- Initiate a strategy/pathway (annotated theory of change) to engage stakeholder and partners at the national level with support by external agency, as needed, to create a shared vision of development needs and processes for scaling
- Study Pigeon Pea and Cowpea relays in P-Sorghum extending seasons

2.1.3. Biotic challenges for both AS and PS

AS is affected by a wide range of constraints, notably drought and climatic variability, diseases (e.g., Anthracnose), weeds and bird damage after grain set, and poor-quality seed and other inputs, as well as distant and poorly developed grain or forage markets.

2.1.3.1. Rhizomatous-PS becoming a pernicious weed

As is the case for potential benefits (2.1.1. above), the risks are not well understood. There is, as yet, no thoroughly field-tested rhizomatous-PS in existence. In theory, the greatest concern is the possibility that Rhizomatous-PS, capable of remaining viable during the long growing season, could become a pernicious weed, and perhaps difficult to manage across cropping systems. An example of this risk is the case of Johnson grass (*S. halepense*) that is the plague weed of Southeastern USA and elsewhere. Having rhizomes, rhizomatous-PS may survive long dry-seasons vegetatively and spread rapidly, as mechanical tillage breaks up the rhizomes and enables rapid vegetative propagation of the weed within fields and farms. Great care will have to be taken in host countries where rhizomatous-PS is under breeding and on-farm testing.

> ‘Johnsongrass’ has the rare distinction of being both a noxious weed in 20 U.S. states and an invasive species in 16 (Quinn et al., 2013). With at least 24 herbicide-resistant biotypes now known (Heap, 2012), Johnsongrass appears likely to become even more problematic in the future. For example, a glyphosate resistant biotype discovered in Argentina in 2002 covered 10,000 ha by 2009 (Binimelis, et al., 2009). Its ability to cross with sorghum despite a ploidy barrier (reviewed in Warwick and Black, 1983; Tang and Liang, 1988) makes Johnsongrass a paradigm for the dangers of crop ‘gene escape,’ and restricts deployment of many transgenes that could reduce the cost and increase the stability of sorghum production. Source: Paterson, et al., 2020

> “Rhizomes, subterranean stems that store carbohydrates and spawn clonal propagules, have growth correlated with reproductive, rather than other vegetative tissues, and increase survival of both temperate cold seasons and tropical dry seasons.”(Paterson et. al., 2020)

Until proven otherwise scientists must be mindful that rhizomatous PS might itself become a serious weedy pest. Conventional sorghum’s relative, *S. halepense* (Johnsongrass), is considered a major weed in many parts of the world. It is now known that *S. bicolor* and *S. halepense* are naturally intermating in USA (Rooney, 2022), and there are serious concerns that future breeding-derived weeds may be increasingly more difficult to control with herbicides (Tienstra 2022, Rooney 2022, Francis 2022: pers comms). Given the concern about possibly introducing a crop that becomes a weed due to strong rhizomatousness, breeders may be able to create less risky progeny. For perennial rice (see Chapter 3), short rhizomes are believed to enable the crop to survive short dry seasons, long enough for most hydromorphic soil environments in SSA. To what degree short rhizomes in PS would enable long dry-season survival and lower risks of weediness is untested.

While the weediness concern is very real and must be watched carefully as PS is developed and promoted, experienced African weed scientists have informed that Johnsongrass is not considered a significant weed in the long dry season sorghum lands of SSA (D. Chikoye & F. Ekeleme, pers. comm. 2022). Why not? Johnsongrass has been in Africa for millennium. One ponders, is it because even with rhizomes Johnsongrass cannot survive the long dry season vegetatively? Or is it because dry season termites destroy the rhizomes with their vegetative buds? Or is it something else entirely? Growing rhizomatous sorghum relatives in isolation plots might be a very revealing preliminary study.

2.1.3.2 *Striga*

A second concern is control of the parasitic weed *Striga*, present in many African countries. Striga is an obligate, root-parasitic flowering plant that draws its moisture and nutrients from sorghum roots, inhibiting plant growth and reducing yield. Important species occurring in Africa include *Striga hermonthica*, *S. asiatica*, *S. aspera,* and *S. forbesii. S. asiatica* can also be a major constraint limiting yield in Asia (Reddy, et. al., 2012). Were *Striga*-susceptible rhizomatous-PS to be planted in low fertility environments and kept in the field for three seasons, or more, the infestation of *Striga* would likely become huge and unmanageable. One *Striga* plant can drop a thousand seeds in the soil that can survive 10 years, or more. Building on early research of Dr Gebisa Ejeta, *Striga* resistance genes that mitigate infection have been transferred to improved AS cultivars through conventional breeding approaches (pers. Comm. Eva Weltzein, 2022). Though this may require repetitious selection in rhizomatous-PS, it is not expected to present a long-term constraint. Four or more years of backcrossing and seed multiplication could be required. Backcross insertion of the rhizomatous character for dry-season survival into adapted *S. bicolor*, which already has *Striga* resistance, could be a good approach. This assumes that rhizomatous-PS, such as those selected by Cox in 2016, can survive the long dry season in sorghum zones.

2.1.3.3 Termites

Another concern that merits further investigation is to determine to what degree termite damage will drastically reduce rhizomatous-PS plant stands during dry seasons. Clearly, in infested fields (very prevalent in the SSA semi-arid savannas) termites remove nearly all dry mater from soil surfaces during the dry season. One observation is that genotypes with “stay-green”[5] trait expression have less early damage from termites (Nebie, Pers. Comm., 2022). Will termites also damage rhizomes? Or will viable rhizomes, escape termite attack? If rhizomes are damaged, serious investment of termite control needs consideration. Testing rhizome survival under controlled experiments with termites should be conducted, perhaps using Johnsongrass as a surrogate, or using the rhizomatous diploid breeding line from The Land Institute (TLI).

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[5] With the stay-green genes, sorghum plant maintains green leaves and stems well past seed maturation. Feed nutrition quality remains good, and breeders are combining stay-green with “brown midrib” genes for superior feed digestibility.

2.1.3.4. Birds

In much of the semi-arid savanna biome of SSA small birds such as *Quelea quelea* (https://www.cabi.org/isc/datasheet/66441) are major pests. Damage from these huge flocks is somewhat mitigated when there are large areas of sorghum and/or millet with synchronous ripening and harvests. But were there only a few farmers who have early grain production from rhizomatous-PS, the bird damage could be devastating. Even, early maturing varieties are at risk of total grain loss from birds in W. Africa (Nebie, pers. com., 2022). To date there are not successful control methods. This problem may demand that short-day photoperiod sensitivity be included in rhizomatous-PS varieties—so they flower only when native medium maturity sorghum is also flowering—especially for areas where *Quelea quelea* or similar bird pests are present in large numbers.

2.1.3.5. Disease and Insect Pests

There are several fungal diseases that have been receiving attention of Sorghum breeders in Africa. The principal ones include head smut (*Sphacelotheca reiliana (*Kühn Clint) and anthracnose (*Colletotrichum sublineola)*. Authors suggest harnessing broad horizontal resistance for many races and other fungi as well. Sorghum downy mildew (SDM) caused by *Peronosclerospora sorghi* (Weston, Uppal and Shaw) is a serious disease of sorghum. Out of 16,000 world sorghum collections screened at ICRISAT only about 130 accessions were resistant against the SDM pathogen (Pande, et. al., 1997). Kamala, et. al., 2002) reported 36 potential sources of resistance against this fungus from wild species of sorghum. Members of the tertiary gene pool, representing Chaeto-, Hetero-, Stipo-sorghum, and the Australian Parasorghum, are reported to be immune to the disease (Kumar in Rakshit, 2016).

The sorghum Grain Mold Complex (GMC) is a serious quality concern that mostly manifests itself in West Africa if the crop matures when rainfall is still occurring. *Fusarium* is a principal component, but many saprophytic fungi contribute. It is more often a problem associated with the bold-seeded durra types, such as those grown for food in Nigeria and Niger (Nebie, pers. comm. 2022). Small-seeded types with open panicles are less prone to GMC. When possible, the incorporation of the rhizomatous trait should be based on germplasm with resistance or tolerance to major diseases.

Stem borers are endemic in all sorghum growing areas. Head bugs, shoot-bugs, midges, mites, and sugarcane aphids limit the crop yield in varying intensity, depending on the location, season, and other prevailing climatic and edaphic factors. IPM approaches should be studied to optimize economic return to farmers and minimize pesticide exposures and unintended environmental insults.

2.1.4. Socioeconomics challenges

Several socioeconomic constraints can be identified for PS. In SSA, the seed system and the availability of quality seed in which farmers could have confidence is one potential leading constraint. Second, produce markets and pricing will be a key consideration. While value chains are relatively well developed for annual food grain in about half of the Agropastoral FS (e.g., southern Zimbabwe, western Tanzania, northern Nigeria, north of Kano, and southern Burkina Faso/northern Ghana), the same cannot be said for extensive areas of other large sorghum growing areas such as Mali, Sudan, Chad and Niger. If the grain quality of the PS resembles the AS, consumers may well accept the grain without price discounts. In the half of Agropastoral FS without reasonable market access, farm gate prices will generally be lower and dependent on the season and local markets or exchange.

As noted above the lack of functioning forage markets is another potential constraint to dual purpose PS. But the fodder demand for fattening goats at times of celebrations creates a surge in feed demand around peri-urban zones, as well as the opportunities for exports mentioned above. Opportunities for fodder income are expected to expand in the foreseeable future.

2.2. Main Potential Benefits

Multiple potential benefits of P. Sorghum for household food security of producers include: increased farm and value chain income from higher yields; increased biomass production for livestock feed and forages; potential increased resource- and input-use-efficiency; reduced soil erosion and increased soil health; and strengthened resilience to climatic variability.

One main potential benefit of a shift from functional annual to rhizomatous-PS would be reduced labor. Land preparation and planting would probably only be done once in every 3 or 4 years. Interviews of farmers in Mali support the hypothesis that from the labor-saving aspect, women and children would be principal beneficiaries of rhizomatous -PS adoption (Rogé et. al., 2017). Another important advantage is reduction of the yield loss from late planting of AS or other major crops in the farming system, which is very common because land preparation and timely planting are very difficult using family resources. P-sorghum ratoon shoots from the crown or from rhizomes will likely emerge vigorously at the onset of first major rains. The resulting rapid stand-establishment will also help the crop compete with weeds and should reduce the cost of weed management. The deep roots will enable rhizomatous-PS to extract soil moisture and nutrients more effectively to better withstand stress. Furthermore, where grazing of sorghum stover during the first half of the rainy season occurs, rhizomatous-PS will likely be an attractive choice for farmers with livestock or for selling PS fodder – with higher digestibility than natural pastures — in addition to grain. Lastly, PS will greatly reduce soil erosion in hill-lands, such as those common to Ethiopia, Kenya, Uganda, Rwanda, etc.

> "Perennial grain systems may relieve the labor bottleneck for women by reducing the need for soil tillage and the frequency of sowing. There may also be a long-term reduction in weed issues in truly perennial grain systems, especially if the perennial grain crop can establish early in the season with the first rains, and thus compete effectively with mostly annual weeds."
> Source: Rogé et. al., (2017)

These advantages, in theory, will reduce costs and risks of production, which in turn, could enable family farmers to apply more nutrient inputs. Yields would be expected to increase. Financial benefits to the farm family will be significant. Rogé et. al., 2017, summarized the cases for P-sorghum made by others: Armstrong, Glover, Reganold, and Cox, 2010; Cox et al., 2002; Cox, Glover, Tassel, Cox, and DeHaan, 2006; Cox, Picone and Jackson, 2004; Crews and DeHaan, 2015; Glover, 2005; Jackson, 1980; Jackson, 2002; Wagoner, 1990. Soil health and water-use efficiency will be enhanced by increases in below-ground biomass and soil organic matter in rhizomatous -PS systems, where soil disturbance from plowing is minimal. This, in turn, may reduce the negative impact of Striga. Striga effects on infested crop productivity are greatest in low fertility environments. Loomis (2022) however, questions the hypothesis of benefits from perennial conversion of annuals due to yield loss trade-offs, disease and pest build up. Loomis did not acknowledge the potential benefits of erosion control by reducing tillage, especially for sorghum in hill-land topographies.

The additional value from rhizomatous-PS's potential multi-cuts of fodder merits note. The early cut or even controlled grazing of rhizomatous-PS comes at a time when minimal browse is available in the semi-arid savannas. Biomass from the second cut can be fed to confined ruminant livestock or converted to silage for use in the dry season (Glover et al., 2010). One can easily imagine more resilient FSs based on rhizomatous-PS sown together with perennial food- and/or forage-legumes, such as pigeon pea and cowpea. This agronomy, however, cannot be tested thoroughly until there is a rhizomatous-PS able to survive the long dry season (6-8 months).

Sorghum production needs to be linked to industries to add higher returns to the sorghum farmers. Decentralized livestock feed mills hold promise for rural communities if energy prices for processing can be made economical. With favorable policy support and accompanying breeding efforts, this crop is likely to expand in drier cropped zones of SSA.

The major benefits from PS can be summarized as:

- Increased and more reliable food supply
- Farm and rural community income

- Forage and grain for livestock
- Increased resource use efficiency (labor, costs, nutrients, soil moisture, etc.)
- Increased system resilience/reduced risk
- Environmental/reduced soil erosion

An additional consideration to explore would be to develop a perennial sweet sorghum, which would be similar to sugar cane, but adapted to drier ecologies[6]. There are new methods for producing hybrid sweet sorghums that are grain-less. Seed for planting would probably need to be purchased every 4 or 5 years. Such annual sweet sorghum has been developed by scientists at Texas A&M University (B. Rooney, 2022 personal communications). These new sweet sorghums require minimal N fertilizer as they do not produce grain. Sugar juices are expelled from stalks, which then can go directly, without intermediate enzymatic processes, into fermentation and distillation for bioethanol production. This sugar-based bioethanol could, like biodiesel, be efficiently produced at large farm or community level. After crushing, stem residuals could be fed to livestock for feed energy. This potential diversification opportunity of perennial sweet-sorghum could be of huge economic merit for the energy-poor Agropastoral FS rural communities and cities which currently face very high energy prices because of high import and road transportation costs from coastal ports, and thus inexpensive energy would likely be transformational.

One other opportunity for PS, and perennial legumes such as Stylosanthes, Progardes Desmanthus, Desmodium (one species protects against Striga) and even pigeon pea, is to explore the regeneration of degraded crop or rangelands, by seedball technology where PS and the perennial legume seed would be pelleted with sand, loam, and wood ash and Phosphorus. Seed balls could be distributed by various means (including airplanes, drones or from horseback) at the start of the rainy season. Seedball technology is currently in use in Australia and has been explored by Kansas State and Hohenheim Universities, funded the USAID Feed the Future Program.

2.3. Best fit farming systems

2.3.1 Adoption and scaling pathways

There are three major pathways to adoption of PS: 1) replacement of AS, 2) replacement of other crops especially millet and perhaps maize in marginal areas after climate change, 3) use as a pioneer

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[6] Rooney et.al, 2007, Designing sorghum as a dedicated bioenergy feedstock. Published online in Wiley InterScience (www.interscience.wiley.com); DOI: 10.1002/bbb.15; *Biofuels, Bioprod. Bioref.* 1:147–157 (2007)

crop for new cropland – see Chapter 4). The first and the third pathways are expected to be most important for PS adoption and scaling. The key drivers of adoption for PS will be increased grain and forage production, labor savings in second and subsequent seasons, risk reduction and increased climatic resilience. The increased and more reliable grain yield will improve household food security and incomes, especially in the huge Agropastoral FS, and in the substantial drier subzones of SSA's Cereal Root Crop Mixed FS and the Maize Mixed FS. A fodder cutting prior to grain production will be very attractive for many farm families. Potential drivers for adoption of PS through the first pathway, the AS replacement pathway, are listed in the Table 2.2.

Table 2.2. Drivers of PS Adoption by Smallholders

	Perennial Sorghum cf. Annual Sorghum	Notes
Grain yield/ household food security	At least 15% greater yield over three seasons but with 20% additional net income from reduced labor and risks; income; reduced labor and risks. Median yield 1.5 to 2 T by 2035 on-farm trials/seed multiplication	Food security also more reliable as PS will be less vulnerable to erratic onset of rains, and timely plant establishment will be secure.
Grain Quality	Grain size is more important in Nigeria and Niger, also generally true in South Asia. At onset of development slightly smaller grain size is probable but acceptable to market Specific organoleptic parameters will not be insurmountable.	Smaller grains will likely have slightly higher protein content but protein production per ha will not be increased. Feed mills won't care. Low tannin in seed testa is important in all grain & dual-purpose sorghums.
Stover Quality and Quantity	Stay Green and brown midrib traits will be in the recurrent parents. Biomass will likely be 10% more. Fodder cut at 3T/ha and with 1.5T/ha grain	Stover quantity & quality is very important in both the semi-arid fraction of the Cereal Root Crop FS, as well the Agropastoral FS
Permanence	In both FSs only one yearly grain crop is expected for three years. During the second and third rainy seasons, one or more fodder cuts or grazing event will occur.	Total biomass and less tillage will ensure more feed and more soil quality with flora and fauna increases.
Crop Management and Soil Health	Similar to continuous AS, except for lack of ground preparation and seeding in two seasons. Possible advantage for applying tied ridges for water harvesting but likely have greater weeding costs.	Total biomass and less tillage will ensure more feed and enhanced soil quality with flora and fauna increases, plus better rainfall infiltration

Table 2.2 also illustrates the most important adoption pathway for PS in South Asia through replacement of AS, benefiting from labor savings, reduced establishment costs, greater resilience and potentially increased farm grain and forage yields.

The second and third adoption pathway depend on a balance of reliable food security, trade-offs between crop income and risk and general fit into the farming system, i.e., integration into rotations or balancing labor and cash requirements through the year.

2.3.2. SSA farming systems

The best opportunities for PS are in the Agropastoral FS in SSA and the drier cereal-pulse sub-system of the Cereal Root Crop Mixed FS, with secondary but important opportunities in the drier zones of the Maize Mixed FS (and possibly in some limited niches of better soils with run-on water in the Pastoral FS). Generally, sorghum is, and will likely continue to be, primarily produced in agroecologies or fields where maize cannot be reliably grown due to insufficient reliable rainfall, sandy soils, or other constraints.

The largest areas of these "sorghum" ecologies have long dry seasons (6 to 8 months), but there are less important but more favorable sorghum growing areas in the Maize Mixed and Cereal Root Crop Mixed FSs with shorter dry seasons. PS would have to compete with maize, cassava and other food and cash crops in such areas. PS could likely replace some cassava but not likely much maize ground, in the absence of severe climate change or pest and disease issues. However, it is expected that PS would replace some millet, especially in the Agropastoral FS. Moreover, sorghum is known as a good pioneer crop in newly cultivated land.

Table 2.3. Plausible Adoption of Perennial Sorghum in Farming Systems in Sub-Saharan Africa

Farming System	LGP (d)	CultArea (m ha)	Animals (m tlu)	Agricpop (m)	*Proportion (%) 2030/ 2040/ 2050	*Area (m ha) 2030/ 2040/ 2050
Agropastoral	**130**	**60**	**69**	**87**	**Na**	**Na**
Dry semi-arid	<120	20	23	29	0/ 0/ 1	0/ 0/ 0.4
Moist semi-arid	>120	40	46	58	0/ 1/ 5	0/ 0.5/ 2.5
Maize-Mixed	**196**	**40**	**36**	**107**	**Na**	**Na**
Moist semi-arid	<180	8	7	21	0/ 0.5/ 3	0/ 0/ 0.3
Subhumid	>180	32	29	86	0/ 0.5/ 1	0/ 0.2/ 0.4

Cereal Root Crop Mixed	**187**	**34**	**29**	**43**	**Na**	**Na**
Moist semi-arid	<180	5	4	6	0/ 0.5/ 3	0/ 0/ 0.2
Subhumid	>180	29	25	37	0/ 0.5/ 1	0/ 0.2/ 0.4
Total	**na**	**134**	**134**	**237**	**Na**	**0/ 0.9/ 4.2**

Notes: Sourced from Dixon et al (2020). The areas and populations o5f the dry and moist subsystems are indicative (see Annex 1 for further detail). Within the Agropastoral FS: dry subsystem is dominated by dry semiarid conditions <120 average growing days (agd); moist semiarid is dominated by most semiarid conditions > 120 agd. Within the Maize Mixed FS: Within the Maize Mixed FS and the Cereal Root Crop Mixed FS: drier subsystems are dominated by moist semiarid conditions <180 agd; moist subsystems are dominated by subhumid conditions > 180 agd. The distribution of cultivated area, livestock and agricultural population across the subsystems is based on the subsystem data in Dixon (2020) and expert judgment. *Adoption (%) and *Area (m ha) refer to estimated cultivated areas for 2030, 2040 and 2050 (see Annex 1).

Although small numbers of farmers might continue with the traditional ratooning of AS, it is expected that new PS lines would not become available for distribution and seed system development until the mid-2030s. Consequently, adoption levels in 2035 would be minimal. However, if the earlier-described product profiles of PS are developed by breeders, and seed system, financing and extension programs are launched, then adoption could be underway by 2040 – by which time climate change will be impacting farmers, transport infrastructure and markets will be better developed and forage and feed markets will be common across Africa, stimulated by increased consumer demand for animal and fish products. Under such circumstances this preliminary analysis suggests that PS adoption area could be of the order of 2 – 5 % of cultivated area, depending on the FS amounting to more than 8 m ha across SSA, of which half would be in the moist semiarid subsystem (with more than 120 growing days in average seasons) of the Agropastoral FS. Adoption rates would increase during the 2040s driven by expanded livestock and industrial demand with a plausible adoption area of 20 million ha across SSA. Farmers would benefit from improved food security, increased net farm incomes and reduced labor requirements especially for women. With the elimination of cultivation after the establishment year, soil erosion will reduce despite increased intensity of storms from climate change and there is potential for increased soil carbon sequestration and the sale of carbon credits. Should perennial sweet-sorghum bioenergy cultivars be developed the Agropastoral FS might have a transformational new bio-ethanol industry based on new low N requiring sweet-sorghum. This argues for a wider investment in sorghum breeding and agronomy for SSA. Should perennial growth habit also confer weediness reduction in development of PS will likely be curtailed.

2.3.3. South Asian farming systems

Sorghum has been a traditional crop in South Asian rainfed farming systems, concentrated in the Dry Rainfed and the Rainfed Mixed FS in central India. Given the biomass scarcity and dependence for milk and chicken, forage markets are well developed and the income from forage is a major portion of the value of production from sorghum. Pearl millet is a competitive dryland crop which has benefited from substantial crop improvement, including hybrids. Table 2.4 contains a preliminary analysis of plausible adoption.

Table 2.4. Plausible Adoption by Farming Systems in South Asia

Farming System	LGP (d)	CultArea (m ha)	Animals (m tlu)	Agric pop (m)	Adoption (%) 2030/2040/2050	Area (m ha) 2030/2040/2050
Rainfed Mixed	-	86.5	112	269	0/2/4	0/1.7/3.5
Dry rainfed	-	10	15	63	0/3/10	0/0.3/1
Total	**-**	**97**	**127**	**332**	Na	0/2.0/4.5

Notes. Adoption (%) and Area (m ha) refer to cultivated areas for 2030, 2040 and 2050 (see Annex 1).

With moderately strong service providers and value chains, in the traditional sorghum concentration area where sorghum is a high proportion of the cropping system in the Dry Rainfed FS the adoption potential would be 3% by 2040 and 15% by 2050 driven by the increased yields and reduced laborneeds. Adoption would be slower and more dispersed in the Rainfed Mixed FS where sorghum has traditionally been a rotation crop. In sum, the potential adoption in 2040 could be 2.3 m ha and in 2050 as much as 11 m ha. Farmer benefits would be, in order, reduced risk, farm income and household food security. The substitution of PS for AS would improve soil health.

2.4 Research and Development

A stepwise decision tree approach is logical to enable prioritization and planning of investment in PS research for SSA and is introduced in Chapter 4. Early actions include screening *S. bicolor* germplasm for survival of stem-crown vegetative nodes over 5 to 8 months dry season (this should be done with and without termite pressure). At the same time, rhizomatous sorghum relatives should be tested for long dry season survival. Progeny from wide crosses should also be included in this initial screening.

If any *S. bicolor* entries show strong survival under long dry season pressure, the efforts to transfer rhizome-based survival can likely be discontinued. If not, wide crosses will be the probable pathway, but only if *S. halepense* or *S. propinquum* survive long dry season stress. Should existing wide cross progeny for TLI show long dry season longevity, studies should begin to determine if they can be used as donors for subsequent recombinations. Potential weediness studies must keep pace with these efforts in gene transfer.

Many very important traits must be combined with long dry season survival and as many a possible should be combined in what will become the recurrent parent in a backcrossing program. Examples would include traits shown in figure 2.1 above.

If and when functional PS exists combined with the most essential agronomic traits, the studies to tune agronomic practices and supporting economic services should be launched. The synthesis and way forward for R&D for PS is provided in Chapter 4.

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CHAPTER 3

Perennial Rice

3.0 INTRODUCTION - CONSTRAINTS AND OPPORTUNITIES OF ANNUAL AND PERENNIAL GRAINS

Perennial grain crops have been proposed to reduce environmental degradation associated with agricultural production systems based on annual grain crops (Glover et al. 2010a, b). Wide hybridization between related annual and perennial species commenced in Russia in the 1920s (Tsitsin and Lubimova, 1959; Wagoner, 1990), but early efforts lacked floret fertility and had undesirable agronomic traits. Successful hybrids were later reported in rice (Tao and Sripichitt, 2000; Sacks et al., 2003, 2006; Hu et al., 2003, 2011) and other crops (Cox et al., 2006, 2010), with capacity to both regrow and set seed providing the opportunity to commence selection. Research in perennial wheat (*Triticum aestivum* 6N/wheatgrass (*Thinopyrum intermedium* 6N)) demonstrated the difficulty in dealing with complex genomes (e.g., Bell et al. 2008, 2010; Hayes et al., 2012, 2018; Larkin et al., 2014). In contrast, both parents in perennial rice (PR) were 2N and AA cytoplasm and were phylogenetically close. Substantial progress has now been made in PR (Zhang et al., 2017, 2019, 2021; Huang et al., 2018; Samson et al., 2018; Zhang et al., 2022). Four years of cropping with PR increased SOC, Total N and PAWC, and in 2021, PR was grown on 15,333 ha by 44,752 smallholder farmers in southern China. Three PR cultivars have now been released in China (PR23, PR25, PR107) and one PR cultivar has been released in Uganda (PR107).

Annual grain crops were first domesticated in the Neolithic period (Scott, 2017), with their annual habit conferring a greater sink priority to grain formation, in the absence of a need to invest in regrowth capacity (axillary buds, tillers, stolons, rhizomes, roots) for the next cycle (Loomis and Connor, 1992). Their higher grain yield and input efficiency relative to traditional landraces ensured their dominance under cultivation, but also ensured ground cover was intermittent, which was associated with losses of soil, nutrients and soil organic carbon (SOC), thereby compromising ecosystem services (Crews et al., 2018). In contrast, perennial crops with deeper roots could increase nitrogen retention and SOC accumulation, improve labor efficiency and system flexibility by contributing both grain and forage for livestock, while retaining soil cover and reducing nutrient and soil loss, thereby maintaining ecosystem functions (Culman et al., 2013; Jungers et al., 2019). Nevertheless, perennial grain crops could pose additional challenges, such as nutrient immobilization with larger below-ground dry matter, control of weeds in undisturbed ratoon stands in the absence of cultivation, greater pest or disease incidence with continued infection in regrowth cycles or from previous stubble, and difficulty in removal after several cycles, in order to rotate to another crop or pasture. These potential constraints to perennial grains are examined, together with the strategies available to reduce their risks, in sections 3.3 and 3.4 (Zhang et al., 2022).

3.1 CURRENT STATUS OF PERENNIAL RICE CULTIVARS, THEIR ADAPTATION.

Perennial rice cultivars PR23, PR25, PR107 are released in southern China, and PR107 is released in Uganda. As considerable evidence is already available on their performance, adaptation and grain quality, this initial section examines what is known and how it potentially relates to target environments and farming systems in Sub-Saharan Africa, South Asia and Southeast Asia.

3.1.1 Current perennial germplasm

A successful interspecific hybridization between the annual domesticated Asian rice *Oryza sativa* ssp. *indica* RD23, a cultivar from Thailand, and an accession of the undomesticated African perennial and rhizomatous *O. longistaminata* from Nigeria was achieved by embryo rescue in 1996 (Tao and Sripichitt, 2000). The F1 plant possessed strong rhizomes, partial floret fertility and self-compatibility, which provided foundational material for development of perennial rice.

An exceptional F2 individual (1 in 7200) was selected with 85% pollen fertility and 60% seed-setting rate in 2007. Cycles of self-pollination and selection (for short rhizomes, regrowth, seed set and agronomic type) followed, to develop plant types resembling the domestic annual rice (AR) parent, while retaining the regrowth capacity of the perennial parent (Zhang et al., 2014; 2017). PR23 was released in 2018 (Zhang et al., 2021), and only 16.16% of the PR23 genome was from *O. longistaminata* (Zhang et al., 2022). An earlier-maturing sister line, PR25, was released in 2020.

In a second round of breeding, a perennial rice breeding line was back-crossed three times with the elite *indica* cultivar Dianrui 449, followed by several cycles of self-pollination and selection. PR107 was released in 2020 in China and in 2021 in Uganda. Performance, genotype by environment interaction, patterns of adaptation, heritability, response to selection, agronomic requirements and soil benefits are also reported (Zhang et al., 2017; 2019; 2021; Huang et al., 2018; Samson et al., 2018; Zhang et al., 2022).

These results indicate that the breeding strategy, based on large population size and strong selection for perenniality and pollen fertility in F2-derived recombinant inbred and backcross populations, was highly effective (Zhang et al., 2022).

3.1.2 Irrigated and favorable conditions

Under favorable conditions in southern China (2016-2020), PR performed similarly to re-transplanted AR in bunded fields for up to 8 successive seasons over 4 years, with each crop yielding about 6.80 t ha^{-1} on average (Zhang et al., 2022). Nevertheless, grain yields were higher in the first (dry) season with greater solar radiation (7.84 t ha^{-1}) than in the second (wet) season which is cool, cloudy and wet (5.76 t ha^{-1}), with grain yields declining over ratoon cycles by about nine percent per year within both seasons from year 1-4. Yields then decreased sharply by about 3 t ha^{-1} in the fifth year, suggesting a need to replant in year 5 in southern China. These data derive from large-scale on-farm testing in Xinping, Menglian and Mengzhe in Yunnan Province of China (altitudes 600, 960 and 1255 m respectively), at the Tropic of Cancer (23^{o}N). These crops were irrigated paddy, with a basal dressing of 36-90-72 kg NPK ha^{-1} applied at planting, and split applications of 72-72-36 kg N ha^{-1} applied at tillering, boot and boot plus 15 days in each cycle.

Much of the Large-Scale Irrigated FS in SSA (see Chapter 1 and Annex 1 for characteristics of the target farming systems) borders the Sahara Desert, so is likely to encounter high temperature and high vapour pressure deficit (VPD), thereby reducing grain yield potential of both AR and PR to about half, say about 4.0 t ha^{-1} and 3.0 t ha^{-1} on average in first and second seasons. Between ratoon cycles, PR plants must be able to access available soil water, or persistence of PR will decrease dramatically especially if temperatures are high (Samson et al., 2018). Irrigated rice is also grown under various water management regimes, designed to save irrigation water without sacrificing yield potential, while perhaps reducing greenhouse gas emissions (Fukai and Wade, 2021). The alternative regimes include Aerobic (flush irrigated to maintain soil saturation without ponding), AWD (Alternate wet and dry, with water ponded and replenished after the soil surface dries), Safe AWD (as with AWD, but rewatered before the water table drops below 10 cm from the soil surface), and Delayed Flood (with ponding delayed until tillers elongate before booting). With good management, these regimes can yield similarly to paddy rice, but even mild water deficit at sensitive growth stages after ponded water vanishes can penalize grain yield (Fukai and Wade, 2021), which is more likely under high temperature and high VPD conditions in SSA unless irrigation management is of high standard. Hence, it may be safer to grow AR and PR under paddy irrigation with ponded water, rather than in water-saving regimes.

These principles should also apply to the favorable rainfed lowlands which occur in many other farming systems in SSA, SA and SEA, where ponded water should be present through critical growth stages, and periods with too much water (submergence) or too little moisture (water deficit) are unlikely, perhaps on hydromorphic soils or those with greater water-holding capacity, and sufficient rainfall.

3.1.3 Rainfed lowland, flood-prone, and rainfed upland conditions

There are two important fields trials of PR which provide foundational results on PR performance in several target farming systems in SSA, one rainfed trial in Uganda and one irrigated trial in Cote D’Ivoire-Senegal. In Uganda over 11 sites (Wakiso, Oyam, Kasese, Buguri, Butaleja, Soroti, Alebtong, Lira, Gulu, Nwoya, Pakeash), for 2 crop cycles per year for up to 2 years, PR107 averaged 5.90 t ha^{-1} to annual check WITA9 averaging 4.80 t ha^{-1} (Jimmy Lamo, personal communication), for a 22.5% yield increase on average. This was under rainfed lowland conditions, mainly in north, mid-north and central Uganda, and mostly around 1000 m in altitude (980-1115 m) (see Annex 3 for further details). There was a 25% yield increase with PR107 at sites in the north, but a lower percentage in some higher-yielding sites in the east. Interestingly, the biggest yield increase was 50% at a lower-altitude site (Pakwash, 650 m), where flooding may occur. This area in Uganda is a Maize Mixed FS, generally favorable rainfed, with a short (3 m) dry season. Though not tested, there may be potential for spillover into the Highland Perennial system to the northwest and south in Uganda. Rice yellow mottle virus (RYMV) resistance of PR107 was a huge plus, as the reference cultivar Supa from Tanzania, popular with consumers and producers, is now susceptible to RYMV, blast and sheath blight, the three major diseases of rainfed lowland (and irrigated) rice in many areas of SSA (although not Uganda). PR107 had resistance to all three diseases and had better eating quality than the preferred local check, WITA9. Clearly, perennial rice does well in favorable rainfed lowland conditions with short dry seasons. Consequently, PR107 has now been released to farmers in Uganda.

In Cote D'Ivoire and Senegal five perennial rices (PR101, PR107, PR23, PR24, PR25) have been evaluated over two years at M'be, in the Humid Zone in the Cereal Root Crop Mixed FS and Ndiaye, Senegal with Sahel-108 and WITA-9 as checks – note that WITA-9 was also a check in the Uganda trials. Three cropping systems were considered: Rice-Ratoon-Ratoon per year, Rice-Ratoon-Ratoon continuous, and Rice-Rice per year. First crop yields were often 7-8 t/ha, comparable with the checks, but ratoon yields often dropped sharply relative to replanted annual checks (see further details in Annex 3). Dry seasons are longer, drier and hotter than Uganda, especially in Senegal, so it is not surprising there was some reduction in ratoon yield over cycles, despite the provision of irrigation.

These results from Sub-Saharan Africa are consistent with PR doing well in favorable rainfed lowland conditions such as in Uganda, but when higher temperatures and higher VPD are encountered in long dry seasons (>6 m) such as the Sahel, even with irrigation, there is yield decline in ratoon crop cycles, which was consistent with section 3.1.2. Further data on PR performance in rainfed lowland conditions, including under drought-prone, is available from earlier evaluations in southern China and Laos.

Earlier evaluations of PR23 in southern China (2014-2016) were essentially under rainfed lowland, as fields were bunded, the first (F) dry season was supplementary irrigated and the second (S) wet season was essentially rainfed, and all seasons had only a single split-application at boot stage of 72 kg N ha^{-1} in each crop cycle, after the original basal dressing of 189-108-121 kg NPK ha^{-1}.

Under these conditions, ratooned PR (PR23) and re-transplanted AR (BN21) yielded similarly in the first three seasons (7.10 vs 6.87 t ha^{-1}), but in the second three seasons, the yields of PR were significantly lower than AR (2.98 vs 5.30 t ha^{-1}), so that PR yielded about 1 t ha^{-1} lower than AR on average over 6 crops in 3 years under rainfed lowland conditions (Zhang et al., 2019). In contrast, when early PR germplasm was evaluated in Laos (2011-2013), lower rates of fertilizer were used with no split N application, (only 60-30-30 NPK ha^{-1} as basal dressing), and irrigation was applied only to assist dry season survival. Under high temperature and drought-prone rainfed lowland conditions, grain yields were lower even in the first wet season (2.20 t ha^{-1}), dropped off substantially in the second wet season (0.40 t ha^{-1}) relative to replanted AR, and by the third wet season, either no yield was harvested (Zhang et al., 2017) or the plants failed to survive the second dry season (Samson et al., 2018). These results clearly establish that, as conditions become less favorable, the number of ratoon cycles decreases, and their yield is also substantially reduced (Samson et al., 2018).

In SSA, performance of current PR cultivars will vary with climatic suitability. Potential yields similar to irrigated are expected in favorable rainfed lowland (4 t ha^{-1} in first season and 3 t ha^{-1} in second season under research management, depending on whether the rainy season is long or short, with only 1 harvest per year in the latter, but somewhat less under farmer conditions with poorer water crop management. This may be expected in the Maize Mixed FS with an average LGP of 196 days (with a range from 220 days in the moist parts to 170-180 days in the drier parts), and in the absence of submergence exceeding 3-5 days, in the Root and Tuber Crops FS. Water deficit is expected to increase in the drier parts of the Cereal-Root Crop Mixed FS thereby restricting to 1 harvest per year averaging 2 t ha^{-1} for fewer ratoon years, and with year-to year variation increasing as seasonal favorability declines. In lower rainfall FSs, e.g., in the Agropastoral FS, PR may not ratoon for grain yield, but only for valuable forage production.

The Highland Mixed FS, especially in Ethiopia is likely to be rainfed upland, so PR may be useful where rainfall is favorable, but is likely to fail elsewhere in upland, in the absence of selection of PR for such harsher environments as drought-prone rainfed lowland and drought-prone rainfed upland. Likewise, current PR cultivars have not been selected for flood-prone environments, so are unlikely to do well there, unless submergence is less than 3-5 days, so assimilate reserves can meet anaerobic respiration and minimal growth requirements (Ram et al., 2002). For short-term submergence up to 14 days, the Sub-1 gene permits survival with minimal yield penalty and may readily be backcrossed into PR cultivars. For prolonged submergence, a stem elongation strategy is needed for survival, in order for oxygen to be conducted to roots via aerenchyma, such as in cultivar FR13A, though the genetics is more complicated. In some situations, perennial rice may allow an additional grain harvest per year beyond what may be possible with replanted annual rice, as the ratoon crop will be shorter in duration (70 Vs 100 days). Such a bonus harvest, where the wet season is longer or bimodal (e.g., in the moist Maize Mixed FS in East Africa) and not fully exploited by replanted annual rice, may provide a circumstance in which perennial rice can strongly displace its annual counterpart.

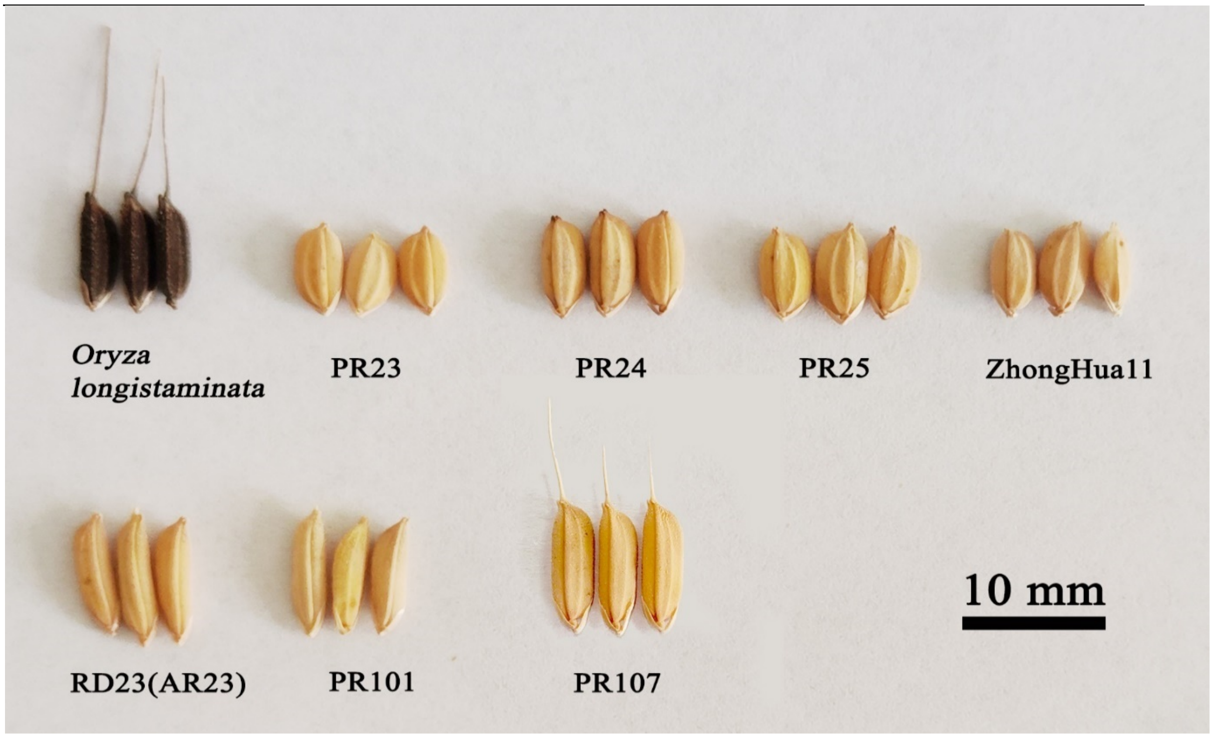
3.1.4 Grain quality

PR23, PR24 and PR25 have grain quality traits similar to typical *O. sativa* ssp. *japonica* cultivar Zhonghua11, including a lower grain length-width ratio of 2.13, presumably obtained from the *O. longistaminata* parent (See table and photograph below). PR107, which was triple-backcrossed to the elite *O. sativa* ssp. *indica* cultivar Dianrui449, has *indica* grain quality, as has PR101, with grain quality similar to its *indica* parent RD23, which had a high grain length-width ratio of 3.57. Unfortunately, PR101 had a low head rice ratio (grain breakage), making it less acceptable to consumers. PR23, PR24, PR25 and PR107 are expected to be widely accepted in Africa, as they are of good (although not premium) quality, similar to current widely consumed rices in Africa: Sahel 108 grown on 70% of the 17.2 M ha of rice cultivation in Africa, and WITA9 which is popular in Cote d'Ivoire. Sahel 108 and WITA9 were imported from Asia, responding to SSA consumer preference generally for Asian-derived rice cultivars, with two exceptions. In Tanzania, the preference is for local aromatic cultivars with long translucent grains, such as cv. Supa. The *indica* PR107 is acceptable grain quality for Uganda and may be closer to requirements in Tanzania. In Ethiopia, rice is consumed in part in *injera* flour mixed with the local preferred grain, teff, rather than as boiled or steamed whole-grain rice, so grain quality requirements for the 62,000 ha of rice in Ethiopia are not clear, though yields of 3.0 t ha^{-1} are reported there. Demand for rice is increasing rapidly over the last 20 years, with Africa importing 16-17 million tons annually worth $2.3 billion.

Perennial rices PR23, PR25 and PR107 are considered suitable for release across a wide range of African environments, based on their grain quality. From preliminary yield testing in 2020 and 2021, PR107 and PR25 performed comparably with Sahel 108 in the Sahel Zone under irrigation (Ndiaye, Senegal), and PR25 and PR23 outperformed WITA9 in the Humid Zone under irrigation (M'be, Cote d'Ivoire), while PR24 and PR101 were lower yielding in both zones. Consequently, PR25, PR107 and PR23 are considered potentially suitable for release as perennial rice cultivars for irrigated and favorable conditions in Africa, based on preliminary evidence of their yield performance and grain quality. PR107 has already been released in Uganda as NARORICE1, because of its perenniality and its resistance to rice yellow mottle virus (RYMV), the major disease of rice in Africa, with this resistance presumably coming from the *O. longistaminata* parent (Zhang et al., 2022). The potential of PR in different farming systems in SSA, SA and SEA are examined more thoroughly in section 3.3.

Table 3.1. Grain dimensions of PR and AR cultivars.

Accession name	Ten-grains length/cm	Ten-grains width/cm	Grain length-width ratio
O longistaminata	8.40	2.65	3.17
PR23	6.80	3.50	1.94
PR24	8.00	3.34	2.40
PR25	7.10	3.50	2.03
ZhongHua11	7.35	3.45	2.13
RD23(AR23)	9.65	2.70	3.57
PR101	9.30	2.80	3.32
PR107	10.40	3.10	3.35



3.1.5 Overall benefits and adoptability for smallholders

In Yunnan China farmers welcome the reduction in labor requirements as well as production costs (Huang et al., 2018), especially when yields and income are similar or better than annual rice. In practice farmers behavior and adoption decisions are influenced by multiple criteria, including their approach to risk and confidence in the performance of the new cultivar or crop. In general, a new cultivar such as PR might replace existing annual rice (the most likely pathway) or replace an alternate crop in a mixed farming situation (less likely during the earlier phase of adoption) or be associated with an expansion of cropped land where land is abundant. Table 3.2 contrasts key areas of benefits and disadvantages of perennial rice replacement of annual rice, which is considered the most important initial pathway for adoption.

In Asian rice-based systems including Yunnan China, the farmers' adoption decision depends on replacing continuous AR (or rice-based rotations) with PR. The principal benefit reported by farmers in Yunnan China has been reduced production costs in the second and subsequent years (Huang et al., 2018) because establishment/seeding/transplanting is not required. So far, 45,000 farmers are growing PR on 15,000 ha under favorable irrigated and socioeconomic conditions in the Yunnan China (Zhang et al., 2022).

Environmental benefits are another key area of advantage for PR. With increasing variability of cropping season rainfall from climate change during coming decades, the year-on-year stability of PR yields is a great advantage for PR, especially in rainfed lowland or upland contexts. During the 1980s/1990s IRRI proposed that the development and adoption of PR would combat and reduce upland soil erosion (Schmidt 1996), as has occurred with perennial pastures. The improvement of soil health from PR is likely not only for uplands, but also in irrigated situations: for example, in Yunnan carbon has been sequestered in irrigated soils over the four-year cycle of PR (Zhang et al., 2022).

We recognized a third area of 'farming system' advantages from PR in mixed farming systems. The saving of rice establishment labor frees up family or hired labor for timely planting on breaking rains of other major rainfed crops, notably maize which would increase yields. Second, any saving of production costs with PR would free up financial resources for the acquisition of improved seed, fertilizer and other production services with an overall increase of total farm productivity. Third, increased yield stability of PR enables farmers to take more risks with inputs and management of others crops.

Table 3.2. Potential drivers of small farmer decision to adopt PR

	Relative advantage of PR over AR	Notes
Grain yield/ household food security	Higher in Season 1 than AR, thereafter equivalent to continuous AR	Primarily evaluated in favorable irrigated conditions in Yunnan China
Grain quality	Slightly lower than continuous AR, but acceptable to producers	Might be fully acceptable in SSA
Permanence	4 years double cropped (8 harvests)	Evaluated in favorable irrigated conditions, and might differ in other environments
Crop management	Similar to continuous AR, except for lack of ground preparation and seeding/transplanting in seasons 2-8.	No research evidence of increased WUE or NUE or buildup of pests and diseases in Yunnan. Conversely, PR might bring tolerance to existing diseases as with PR107 in Uganda.
Soil health	PR has increased SOC in Yunnan China	
Labor requirements	Similar to AR for the establishment season, busubstantially t less in ensuing seasons	
Production costs	Ditto	Dependent on input and market subsidies or other financial incentives
Gross margin/net income	Similar to AR for the first establishment season, but substantially greater for ensuing seasons	
Climate resilience	Increased stability, especially if water scarce or unreliable	
Enterprise flexibility	May allow regenerating annual legumes after wet season rice harvest	PR limits the flexibility to insert cash crops
Replacement for different crop species	Depends	Not applicable in rice-based systems, as in China
Expansion of cultivated area	Depends	Not applicable in most rice-based systems
Key drivers of adoption	Reduced production cost	

3.2 PERENNIAL RICE FIT, ADOPTABILITY AND BENEFITS IN THE MAJOR FARMING SYSTEMS OF SUB-SAHARAN AFRICA (SSA) - SOUTH ASIA (SA)- SOUTHEAST ASIA (SEA).

This section examines farming systems potentially suited to perennial rice in SSA, SA and SEA, drawing from 3.1 to predict where perennial rice may grow, its likely performance, acceptance and prospects for adoption.

3.2.1 SUB-SAHARAN AFRICA

3.2.1.1 Maize Mixed Farming System

In SSA, the sub-humid Maize Mixed system with 40 mha of cultivated land and an agricultural population of 107 m, is potentially a good fit for PR, especially under rainfed lowland conditions and on hydromorphic soil or small-scale irrigated patches, with potential for up to two grain harvests per year. Economically, however, maize is likely to remain the preferred crop, including its rotations with legumes. Adoption of PR is expected to initially be slow, perhaps 2% of farmers by 2030, increasing to 10% by 2040 as back-crossed African PR becomes available, and demand for rice continues to rise. Stubble may also be valuable for livestock, which are important in Maize Mixed. Initial adoption is most likely on hydromorphic soils or small-scale irrigation, where PR (and rice) should have an advantage.

Table 3.3. Plausible Adoption by Farming System in Sub-Saharan Africa.

Farming System	LGP (d)	Cult Area (mha)	Animals (mtlu)	Agric People (m)	*Adoption 2030/40/50 (%)	*Area 2030/40/50 (mha)
Maize-Mixed	196	40	36	107	1/2/4	0.4/0.9/2.0
Root-Tuber	269	23	8	50	0.5/1.5/4	0.1/0.4/1.2
Cereal Root	187	34	29	43	1/4/ 5	0.4/1.6/2.2
Highland-Mixed	183	13	28	45	0.5/1/ 3	0.1/0.2/0.5
Humid-Lowland-Tree	299	8	3	30	0.5/2/4	0.0/0.2/0.4
Irrigated	365	8	23	48	1/2/8	0.1/0.2/0.8
Total						1.1/3.4/7.1

Notes: Length of growing period (LGP), Cultivated area, Livestock numbers and Agricultural populations as of 2015 (Dixon et al. (2020). For estimated rate of expansion of Cultivated areas and Agricultural populations see Table 1.1. *Adoption (%) and *Area (m ha) are for 2030-2040-2050.

3.2.1.2 Root-Tuber Farming System

In SSA, PR should be adapted to this humid zone, which has only a short (3 m) dry season. Initial adoption is most likely where flood risk is low, commencing with 5% of farmers, but rising to 20% by 2040 when back-crossed African PR with the Sub1 gene become available, to protect against risk of short-term (<14 days) local submergence. As consumer preference for rice increases and noting the proximity to many large urban centers, it is expected PR may increasingly displace root and tuber crops, especially as adapted PR become available.

3.2.1.3 Cereal-Root Crop Mixed Farming System

In SSA, PR may have a place in the wetter portion of this subhumid savannah zone, but with the longer (6 m) dry season and higher evaporative demand, the drier portion of the zone is expected to be too harsh for PR. Nevertheless, PR could have a place in these mixed farming systems with livestock, perhaps to stabilize the soils and flexibly contribute to grain for sale, grazing or both. Current genotypes could provide the dual role initially, with say 5% adoption by 2030, and when backcrossed African PR become available, this could increase to say 15% by 2040, as part of the farming system.

3.2.1.4 Highland Mixed Farming System

A niche environment is likely to be available in favorable Highland Mixed farming systems above 1700 m in Ethopia and elsewhere, for PR as an upland crop under milder temperature and favorable moisture conditions. Highland mixed has a diverse crop and livestock mix, so adoption is expected to be gradual, from 2% in 2030 to 5% in 2040.

3.2.1.5 Humid Lowland Tree Crop Farming System

The Humid Lowland Tree Crop system would allow PR production as an alley crop with only a short (2 m) dry season, again as an upland crop. Humid Lowland would suit PR well, with perenniality compatible with tree crops, so adoption is expected to be greater here, from 5% in 2030 to 20% in 2040 as backcrossed African PR become available.

3.2.1.6 Large Scale Irrigated Farming System

In SSA, current PR cultivars are well suited to paddy or safe AWD irrigation, so have biological potential here. But other higher-value crops including cotton and vegetables are likely to take precedence. Only 2% adoption across the irrigated area of 8 mha is anticipated by 2030, while back-crossed African PR may allow this to increase to 10% by 2040. As the large irrigation schemes are often in semi-arid and arid areas, however, ponded water will need to be maintained around heading to flowering and grain set to ensure spikelet fertility. Where annual rice is already grown in these systems, perennial rice may replace it, as cost savings should accrue in ratoon crops, even if cycles were fewer at high VPD. As has been mentioned earlier, small scale irrigation is found in many predominantly farming systems (for example, 5% of the cultivated area of the Maize Mixed FS is irrigated).

3.2.2 SOUTH ASIA

3.2.2.1 Rice Farming System (including Deltas)

In South Asia, the Rice system in East India is high rainfall, and favorable rainfed lowland conditions will again be suitable, but flood-prone areas of moderate or greater water depth (>50 cm) should be avoided. Farming systems are diverse with vegetables and some legumes as well as rice, so initially only small areas will be displaced by PR, perhaps 2% by 2030, with a greater increase to 10% by 2040 when backcrossed PR with the Sub1 gene becomes available, allowing greater penetration into less favored flood-prone areas.

Table 3.4. Plausible Adoption by Farming System in South and South-East Asia

Farming System	LGP (d)	Cult Area (mha)	Animals (mtlu)	Agric People (m)	Adoption 2030/40/50 (%)	Area 2030/40/50 (mha)
SOUTH ASIA						
Rice (Deltas)	-	22.4	-	155	1/3/7	0.2/0.7/1.6
Rice-Wheat	-	61.8	-	302	0.5/2/4	0.3 – 1.2 – 2.5
Rainfed-Mixed	-	86.5	-	269	0.5/ 1.5/ 3	0.4/1.3/2.6
Highland-Mixed	-	18.8	-	63	0.5/ 1.5/ 4	0.1/0.3/0.8
SOUTH-EAST ASIA						
Lowland-Rice	-	91.0	-	488	1/4/9	0.9/3.6/8.2
Upland-Intensive	-	97.0	-	319	0.5/1.5/4	0.5/1.5/3.9
Root-Tuber	-	2.0	-	2	0.5/1/5	0/0/0.1

Notes: Length of growing period (LGP), Cultivated area, Livestock numbers and Agricultural populations as of 2015 (Dixon et al. (2020). For estimated rate of expansion of Cultivated areas and Agricultural populations see Table 1.1. *Adoption (%) and *Area (m ha) are for 2030-2040-2050. *Adoption (%) and *Area (m ha) are for 2030, 2040 and 2050.

3.2.2.2 Rice Wheat

Though well adapted to the Rice-Wheat system, it seems unlikely PR could displace much rice-wheat, especially as a third crop is often harvested in western IGP. Adoption may be only 2% of the area by 2030, perhaps rising to 8% by 2040. PR may increase in importance in eastern IGP, where water supply is less assured and reliance on rainfall is greater, as improved PR become available.

3.2.2.3 Rainfed Mixed

The Rainfed Mixed system already has significant areas of rainfed lowland rice, including favorable, mild drought, and drought-prone areas, as well as cereals, legumes, fodder crops and livestock. PR could be very attractive here, with current PR reasonably well adapted, so adoption could be as high as 10% by 2030, initially in favorable and mild drought, and increasing to 20-25% by 2040, as further improved back-crossed PR become available.

3.2.2.4 Highland Mixed Farming System

Highland Mixed may provide some niche opportunities for PR where temperatures are suitable (not too cold), dry season is short (< 3 m), labor is scarce, and PR grown in the uplands could reduce erosion on sloping lands.

3.2.3 SOUTH-EAST ASIA

3.2.3.1 Lowland Rice Farming System

In Southeast Asia, rainfed lowland areas with shallow water depths from Myanmar and Thailand to southern China in the Lowland Rice system are suitable, with greater adoption likely due current PR cultivars being adapted (RD23 parent) and the importance of livestock. Adoption may be up to 6% by 2030, and perhaps increasing significantly to 25% by 2040. As better adapted PR materials arise from backcrossing, the area is expected to expand considerably into the mildly- and moderately drought-prone areas by 2040.

3.2.3.2 Highland Intensive Farming System

Much greater areas are potentially available in Highland Intensive Mixed in SEA, with similar considerations to SA. Adoption may be 2% to 2030, increasing to 8-10% by 2040. There could also be some spill-over into lower latitudes of Highland Extensive mixed, where upland rice is also grown.

3.2.3.3 Root/Tuber

Though not extensive, the Root/Tuber system in PNG should likewise be a good fit for PR, for the same reasons as in SSA. Adoption is expected to be slow in PNG, due to limited experience and market access.

3.3 CONSTRAINTS AND RISKS

Adaptation of rice (and of PR) is defined by agro-hydrology, water depth and duration, and absence of ponded water (Fukai and Wade, 2021). PR will be subject to additional threats from pests, diseases and weeds, especially in regrowth cycles, but may benefit from lack of soil disturbance for improved ecosystem services. Acceptance by farmers of grain quality, marketability and impact on costs and labor will determine adoption.

3.3.1 Abiotic – Drought and Heat

When considering current limitations and future variability, the three critical questions are: 1) What is the length of the growing period (LGP); will it increase or decrease as a consequence of climate change; will that change the number of crop cycles per year; 2) What is the condition of the growing period (CGP); will drought, heat, (flood, cold), be worse; at what growth stage; what are the consequences for performance; and 3) What is the length and condition of the dry period (LCGP); will it be longer, hotter, drier; will PR survive; will vigor, growth and grain yield be reduced; and for how many crop cycles.

Current PR germplasm has been selected for essentially favorable conditions, so is unlikely to handle significant hot dry seasons, such as those exceeding 3 months in duration, with plants unlikely to survive. This will restrict PR to farming systems with shorter or milder dry seasons, though deeper soils with water available at depth may provide some buffer, but this remains to be properly established. Further, water deficit and heat at sensitive growth stages from heading to flowering and grain setting will reduce spikelet fertility, so yield penalties are expected in more arid environments, even if soil water is available at depth under high evaporative demand. These factors will restrict where PR may be grown for grain, though some contribution to forage or grazing is still possible.

3.3.2 Abiotic – Flood and submergence

Likewise, current PR germplasm has not been selected for performance under shorter- (<14 d) or longer-term (>14 d) submergence. This will restrict PR to environments with shallow (<30 cm) to moderate water depth only (<60 cm), and with limited risk of submergence. Survival under brief submergence (<3 d) may be possible if the plant has sufficient assimilate reserves, but plants will be damaged by oxidative shock on de-submergence, and likely will lodge. While additional water resources are available under flood, it is probably better to avoid those areas with currently available PR germplasm.

3.3.3 Biotic – Pests and Diseases

Pests (brown plant hopper, green leaf hopper, leaf folder) and diseases (rice blast, sheath blight, leaf rust) adapted to high N applications could pose threats under irrigated and favorable conditions, especially in perennial rice, if pustule loads in stubble are large, or insect-transmitted viruses such as tungro become established in regenerating plant crowns. Generally, pests and diseases are of lesser consequence under rainfed conditions, though gall midge may be severe in the absence of ponded water during tiller elongation, and brown leaf spot may be damaging under low soil fertility, but not more so than in annual rice for gall midge and brown leaf spot.

3.3.4 Biotic – Weeds

Relative to re-transplanted rice, in the absence of cultivation, soil puddling, and re-establishment from larger transplants, weed competition will be greater in regrowth cycles of PR. Nevertheless, relative to direct-sown rice, PR should be more competitive with weeds, given its established root system and greater assimilate reserves. Under less favored conditions, however, drought and heat (or flood or cold) may reduce regrowth and may even kill the plant. But if water and nutrients remain available, PR may continue to regrow when the farmer decides to replant, posing a weed threat itself. This may be exacerbated by the presence of rhizomes in PR, though short rhizomes were intentionally selected in PR to reduce the risk of its weed potential. Under irrigation, therefore, tillage may be required to expose the crowns of PR to soil drying, perhaps with follow-up glyphosate spraying of young regrowth if needed before resowing of the next crop.

3.3.5 Biotic – Rats, Termites and Birds

Episodic plagues of rats would threaten PR as well as other crops. Termites damage crops in the dry season, so may pose a threat to regrowth of PR. Out-of-season crops such as a ratoon crop of PR presenting grain outside the normal harvest period may be severely damaged by *Quelea*.

3.3.6 Socioeconomics

Adoption will depend on the balance between labor savings, reduced costs of transplanting, system flexibility and reduced drudgery versus returns from PR. It is important to recognize the low opportunity cost of saved family labor. Reliability of food production is an important criterion for African smallholders (Arounna et al. 2017). For households with limited cash crops, the opportunity to generate cash income from sale of surpluses is also valued, as is the reduction of risk for the whole farm system. In general, a major constraint would be the cost of purchasing PR seed and accompanying crop inputs such as fertilizers and agro-chemicals if available. For many farmers in the early stages of adoption, the lack of functioning markets into which to deliver seed and crop inputs, or from which to purchase surplus paddy, is a major issue. Where active value chains allow acquisition of crop surplus, premium grain quality is expected to generate a higher price and a higher demand in the market. Current PR are of acceptable quality in many countries in Africa, but Tanzania and others prefer aromatic grains such as cv. Supa or imports from Asia.

3.4 HOW TO ADDRESS CONSTRAINTS AND RISKS – WHAT IS NEEDED.

Constraints and risks will be dependent on farming system and intended use of PR. This section explores what is available now, what can quickly be improved by back-crossing and/or by improved management for 2030 adoption, and what strategies are needed to address future climates and longer-term challenges for 2040 and 2050 in target farming systems in SSA-SA-SEA.

3.4.1 Abiotic – Drought and Heat

Currently available PR cultivars (PR23, PR25, PR107) should be adoptable from a biological perspective under irrigated lowland and favorable rainfed lowland, where water deficit is mild and any flooding is limited to waterlogging of moderate water depth without submergence. Most likely, this will be in areas with longer growing seasons (>180 d), which may allow up to two harvests per year. Nevertheless, the dry season may still be up to 180 d or 6 months in duration, so survival of PR to the next growing period may require deeper soils with water-holding capacity at depth, and/or lack of exposure of shoots to high temperatures over the dry season, by protection of axillary buds below the soil surface. Current PR germplasm is not expected to survive hot dry periods in excess of 3 months. When socioeconomic factors are considered, however, higher-value crops should predominate under irrigation, where returns to the farmer should be greater than from rice. Consequently, immediate (2023) adoption is expected to be under favorable or mildly drought-prone rainfed lowland conditions, including on hydromorphic soils, in the absence of submergence and of dry seasons exceeding 3 months in duration.

Back-crossing perennial traits into the popular African rice cultivars such as Sahel-108 and WITA-9 should allow improved PR cultivars to be available by 2030, which should be suitable for a wide range of environments in SSA, given the predominance of these cultivars. The range of environments suited to the new PR cultivars could be further extended by backcrossing the Sub-1 gene for tolerance to short-term submergence, aroma genes for improved grain quality, and flanking markers for genomic hotspots for root traits and yield of rainfed lowland rice under water deficit into perennial cultivars.

Addressing the challenges of PR being able to survive harsh dry season conditions of more than months will require longer-term research, involving selection for dry season survival under conditions of increasing dry season length and severity (heat and drought). Underpinning research is needed to clarify whether rhizomes are essential to dry season survival and growth under such challenging conditions, and whether they threaten weed potential, even with short rhizomes. Likewise, is maximum depth of the crown and the depth from which axillary buds produce a tiller or rhizome a sufficient buffer for survival, especially if plants have deep roots able to tap reserves of subsistence water for survival until the next rains come. Would bud dormancy assist in delaying regrowth until the onset of seasonal rains trigger commencement of the next regrowth cycle or can this be managed agronomically. It would be sensible to avoid green cover during the dry season, not only to reduce water use in the absence of rain, but also to not provide a green bridge for progression of pests and diseases to the next regrowth cycle. For these longer-term goals, germplasm sources likely to encounter harsh conditions should be evaluated, such as aus and tropical japonica, so crossing, selection and backcrossing can proceed in concert with associated physiology, and better-adapted materials for exposure to longer dry seasons, especially under climate change, may be available by 2040, for evaluation and potential adoption by 2050. PR may have an advantage under such harsh conditions, if deeper crowns and roots assist survival, as in other perennial species. This remains to be evaluated experimentally, including trade-offs between perennial and annual habit, and their consequences for resource balance (Zhang et al., 2017).

3.4.2 Abiotic - Flood

Current PR cultivars have not been selected for tolerance of waterlogging, short-term submergence or prolonged flood, so submergence-prone environments should be avoided for initial rainfed adoption. By 2030, however, PR backcrosses to Sub-1 should be available, ideally in African-adapted backgrounds, which will have several benefits. First, plants should be less susceptible to the consequences of inadvertent flooding, such as when rain falls after irrigation. Likewise, in waterlog-prone areas, if a wetter season is encountered, plants will be able to survive any short-term submergence with minimal damage, and this will also apply to regions in which short-term flooding may occur, for periods of up to 14 days. Genes for seedling tolerance of submergence are now being identified (cohorts of Sub-1). Backcrossing of seedling tolerance into PR will have additional benefits for direct seeding and for irrigation, where current rice is vulnerable to shallow early flooding of short duration. Such tolerance to short-term submergence should significantly increase the potential areas suited to PR by 2030, noting that water scarcity is less of an issue in flood-prone areas. Other flood ecologies are expected to be less common, such as deep stagnant flood, flash flood with turbid water, tidal saline, saline and sodic flooding, so may not warrant attention. Where water is stagnant under prolonged flood alone, which is usually associated with greater water depth, it would be possible to back-cross genes for stem elongation from FR13A, perhaps for 2040 if warranted.

3.4.3 Biotic – Pests and Diseases

Pests and diseases of annual rice have been extensively studied, much of which will apply to PR. Under irrigated conditions, breakouts of brown plant hopper, green leaf hopper and leaf folder are associated with high N application but can be managed through integrated pest management with split applications of N more closely matching crop demand. Rust, blast and other leaf and panicle diseases can be severe, but resistance is available in many rice cultivars, and wide hybridization with *O. longistaminata* for perenniality should provide additional resistance. These strategies should also be effective for PR. Under rainfed cultivation, pests and diseases are usually less severe, although gall midge can be important if ponded water is absent during tiller elongation, and thrips can be damaging locally. Perhaps of greater concern are insect-transmitted viruses which would remain viable in crowns, or diseases with high pustule loads such as rice blast able to reinfect from previous stubble. Viruses of concern may include tungro and rice yellow mottle virus, although PR107 is resistant to the latter from its *O. longistaminata* parent, and has been released in Uganda (Zhang et al., 2022).

3.4.4 Biotic - Weeds

Adoption of PR is not without risks to the farmer, as 1-2 more herbicide applications were required in ratoon cycles than in transplanted AR in the experiments in China (Zhang et al., 2022). Short rhizomes were intentionally selected in PR so as not to provide significant weed potential, but to permit improved chances of survival and regrowth when harsher conditions were encountered. While low temperatures in winter or high temperatures and drought in summer may reduce regrowth or kill the plant, perennial stubble may also need to be killed under favorable conditions in order to establish a new crop. Under irrigated or favorable conditions, therefore, tillage may be required to expose PR crowns to soil drying, perhaps with follow-up glyphosate spraying of young regrowth if needed before resowing. Further details are provided in Zhang et al. (2022).

3.4.5 Biotic – Rats, Termites and Birds

Despite their potential severity, none of these were mentioned in focal group discussions in SSA, SA or SEA, perhaps because they have not been encountered in initial PR evaluation.

Episodic pests such as rats may pose a considerable threat to all crops when plagues occur. Crop hygiene, including attention to adjacent grasslands may assist in limiting build-up, but will not address advancing plagues, which would require active barriers and coordinated baiting campaigns.

Experience in sorghum and other crops suggests termites may pose a threat during the dry season by harvest of dead plant materials, though live materials are usually left alone. It is not clear whether termites would harvest dormant below-ground crown and axillary bud material and rhizomes, but if they do, dry season survival for regrowth would have an additional threat.

Birds such as *Quelea* could pose a substantial threat to out-of-season grain harvest, if PR was able to provide an additional harvest when few other crops or grains were available. Netting may be possible for smallholders with limited areas. Bird scaring is possible but very demanding of labor and is generally ineffective. Provision of an alternative feed source in the bush may be useful.

3.4.6 Socioeconomics

The balance between farmer income, costs, labor savings, system flexibility, and risks for particular farming systems will ultimately determine how and where PR is adopted, and how it fits into and contributes to the farming system. Adoption will be favored if market demand and market price are assured by high grain quality to meet consumer expectations. Current PR cultivars have acceptable but not premium grain quality, though PR107 with indica traits may be acceptable in Tanzania and elsewhere where cv. Supa is currently preferred. Backcrossing to preferred African cultivars Sahel-

108 and WITA-9 should provide preferred grain quality quickly, and further backcrossing could add additional aromatic traits. Dual use of PR for forage or grazing may be important post-harvest and at first regrowth where livestock are prevalent, or where conditions are too harsh for grain set in the dry season. Rice stubble is valuable for livestock, despite its higher silicon content, especially if stubble is treated with urea before being fed or is supplemented with some fresh grass or legume forage or maize grain.

3.5 Conclusions

Based on the evidence presented, current cultivars of perennial rice can be adopted now in certain environments: under favorable, mild drought or shallow flood; under RL, RU, FP, Irrigated.

For 2030, back-crossing can provide improved PR in African backgrounds, with additional traits for short-term targeted problems, e.g., Sub-1 (submergence), genomic hotspots (drought), and aroma (grain quality).

For 2040, longer-term crop improvement is needed to provide traits for dry season survival, (dormancy, crown, rhizome, root traits), for drought-prone (& flood-prone) for less-favored RU, RL & FP.

Associated systems considerations (agronomy, longevity, removal, weed control, weed potential, rotation or relay, grain and/or forage) are needed throughout.

The evidence suggests perennial rice is an investment opportunity now.

CHAPTER 4

Conclusions and Recommendations

4.1 Evolving scenarios

Building on the presentations and discussions of the Perennials Grains Convening organized by BMGF ad USAID during April 2022, we engaged in the review of extensive literature and consulted many experts on a variety of aspects such as: climate change projections; state of development of PS and PR; likely target farming system zones for adoption of PS and PR in SSA, SA and SEA; abiotic and biotic constraints; approaches to vegetative survival required for viable perenniality in different contexts; relevant past genetic enhancements; current and future genetic enhancement tools, such as Marker Assisted Selection (MAS), especially for root and crown morphology and physiology, as well as for rhizome trait expression; effective agronomy practices for PS and PR; and cereal adoption and scaling.

We contacted and interacted virtually with more than 75 scientists and development experts – about 30 specialists each on sorghum and on rice and the balance dealing with the adoption and impact of both crops -- and actively sought their comments and advice on preliminary findings through structured focus group discussions at regional and international levels. While recognizing that diverse analyses and interpretations of opportunities and constraints over future decades are possible, our team assessed the opportunities and constraints related to development and impact of PS and PR with the view to inform on the merits of future investment in perennialism and promotion of these two crops.

During the decades of the 2030s and 2040s farming and food systems will be evolving in response to climate change constraints, especially increased volatility, and strengthened market development opportunities – ideally along a sustainable intensification trajectory (Pretty et al 2006; Cassman and Grassini 2020; Dixon et al 2021). In line with the ‘Towards Sustainability’ scenario of FAO (2018), land and labor productivity is estimated to increase substantially by 2050 in SSA as a consequence of biological, mechanical, digital and institutional innovations and improved farm management. As an indication of the order of magnitude of changes, average farm yields for many crops will be 30-50% greater than the past decade (FAO 2018), a majority of harvests will be sold, and most routine crop and livestock management operations will be mechanized – many automated using digitally-controlled equipment – often managed by service providers (Dixon et al. 2020).

Stimulated by expanding and increasingly urbanized population with increased purchasing power and changing food preferences, food markets and differentiate, and food prices are expected to rise (FAO 2018). Furthermore, the demand for feed grains is expected to expand with increasing consumption of animal products, including poultry, fish, milk and red meat. In biomass scarce regions such as rainfed India, the income from fodder can approach the value of income from grain, but analysis of the expected growth and value of the feed grain and fodder markets in future decades needs further study.

The PS and PR crops are at very different stages of development, and most likely face contrasting uptake trajectories and potential roles in transforming agricultural and food systems in the different farming systems of SSA, SA and SEA. PS is at least a decade, may be two, away from developed lines for OFR testing, whereas PR is being grown by about 45,000 smallholders in China and has been officially released in Uganda. Many agricultural scientists in Asia and Africa are showing interest in testing advanced cultivars. The promotion and scaling of these two perennial grains must be viewed in a farming systems and development context. Hence, conclusions and recommendations in relation to PS- and PR based farming systems transformation and for the development of each crop are outlined in the following sections 5.2 and 5.3 respectively.

4.2. Conclusions

4.2.1 Transformation of target farming systems

The farming systems classification and mapping draws on the FAO analysis done originally for the World Bank in order to inform investment strategies for the developing world (Dixon et al. 2001) and updated in detail for Africa (Dixon et al. 2020). Of the 15 regional farming systems and more than 50 subsystems described for SSA, the assessment selected 9 target regional farming systems for detailed analysis of the potential of PS and PR – 3 semiarid systems for PS, and 6 subhumid, humid or irrigated systems for PR (see Table 1.1). A smaller number of target farming systems were chosen in South Asia and South-east Asia, namely, 6 and 3 respectively from the 11 farming systems in each region.

The integration of the perennial crop into the farming system represents a step towards on-farm diversification. The perennial crop brings a set of additional benefits, notably the extra relatively reliable food grain of which a proportion would be sold, savings of labor and production costs in the second and successive years, increased net farm income, extra forage for livestock (especially in the case of dual-purpose PS), increased farm system stability and resilience and environmental benefits in terms of the reduced soil erosion and increased soil organic carbon. The perennial grains would interact with the other crops in terms of land allocation, long term rotations, livestock feed and fodder availability, and labor and cash allocations – and of course both augment the stability or resilience of farm system. The perennial grains do not just augment farm production but could transform the system -- for instance, the savings of crop establishment labor during the second and subsequent years would enable timely planting and weeding of other crops which often suffer yield penalties from late planting or weeding.

The nature of perennial grains enables small scale tests by farmers, say a few rows or a corner of a field, which enables farmer learning and fosters adoption. However, access to information, seed, finance and markets would depend on national scaling programs. It is assumed that initially only part, perhaps one field, of the existing AS would be converted to PS, and likewise for PR.

FAO (2018) and IFPRI (2019) foresight studies to 2050 assume considerable improvement in sector governance and policies that would be pre-conditions for effective national scaling programs in the larger countries in each region. As shown in Chapter 1, increased demand and the continuous flow of innovations provide the basis for sustainable intensification and 30-50% increases in the productivities of most crops – and this 'rising tide' on larger cropped areas would create the conditions for faster adoption in 2040 than has been the historical case.

Table 4.1: Plausible adoption of PS and PR under effective scaling programs

	Perennial sorghum		**Perennial Rice**		
	SSA	**S Asia**	**SSA**	**S Asia**	**SE Asia**
Major target FS	3	2	6	4	3
Potential release of first lines	2035-40	Tbd	2022-2025	2025-30	2023-25
Potential early scaling	2040	Tbd	2030 (UGA earlier)	2035	2030
Plausible adoption (m ha)	2040: 0.9 2050: 4.2	2040: 2.0 2050: 4.5	2030: 1.1 2040: 3.4 2050: 7.1	2030: 1.1 2040: 3.5 2050: 7.4	2030: 1.4 2040: 5.1 2050: 12.2
Initial investment focus	R	R	R, DD	R, D	R, D

Assuming effective PS product development by 2035 and effective national scaling programs in operation in large relevant countries, PS could be adopted on 4.2 m ha in SSA and 4.5 m ha in SA (reversing the current trend of declining AS area). Based on the projected SSA AS yield in 2050 of 1.5 t/ha and the PS product profile of 15% yield advantage over AS, then PS would directly generate an extra 1 m tons of sorghum grain annually by 2050 in SSA and an extra 1.1 m tons in South Asia with significant additional farm family income. Considering the usual S shaped adoption curves, substantial adoption would be expected by 2060.

Given that PR is already released in Yunnan China and Uganda and there is strong interest many NARS in PR, the plausible levels of adoption by 2050 would be 7.1 m ha in SSA, 7.4 m ha in SA and 12.2 m ha in SEA. Based on research results from Yunnan China, Ugandan and Senegal-Cote d'Ivoire a farm level yield advantage of PR over AR of 0.5 t/ha would be plausible which would amount to the production of an extra 13 m tons of rice each year.

In addition, the benefit to the livestock industry in terms of forage production would be considerable but has not been evaluated. The environmental benefits include substantial reduced soil erosion from PS through the avoidance of annual tillage during field preparation for planting AS. Similarly, the improved soil health is expected from PR, and an increase of 0.9 t/ha SOC was measured for PR in Yunnan.

The dynamics of adoption will be different in each farming system, as indicated in Chapters 2 and 3. As noted above, PR development is further advanced (having been released in Uganda and China) than PS (for which adequate lines are yet to be developed, let alone entered in multi-location trials or OFR). Of course, PR would benefit from specific back-crossing during this decade and improved cultivars with wider adaptation could be available from 2030s. PR has the potential for adoption, scaling and economic, food security and environmental impacts in Irrigated systems, where perennial sorghum is unlikely to be competitive. The Maize Mixed FS could benefit this decade from PR availability because of the strong SSA consumer demand and the early release of PR107 in Uganda – and potentially from 2030 from improved PR cultivars and the potential development of PS for the drier marginal FS. Similar benefits could occur in Cereal Root Crop Mixed FS from PR and PS. Both perennial grains might have potential in rainfed (upland) Highland FS. For PR, similar comments apply to SA and SEA as in SSA, with the advantage there has already been some limited testing in India, Bangladesh, Myanmar, Thailand, Cambodia, Laos, Vietnam. Again, some adoption is likely by 2030, with additional benefits accruing with back-crossing, management, and further development. These opportunities need to be analyzed and assessed, and any risk to farming systems from adoption of perennial rice and perennial sorghum needs to be explored.

4.2.2 Perennial sorghum

We posit that in SSA the initial future of PS will be in the same farming systems as annual sorghum dominates today, namely, the Agropastoral FS, the dry subsystem of the Cereal-Root Crop Mixed FS in West and Central Africa and the Maize-Mixed FS in Eastern, Central and Southern Africa. Agronomically superior PS cultivars could begin to replace a proportion of existing AS from the second half of the 2030s. PS is unlikely to replace major areas of maize in favorable environments, climatically and soil-wise – although climate change is expected to reduce the extent of those favorable environments for maize and AS and PS would be natural replacements. Agronomically sound dual purpose (forage and grain) PS cultivars would be competitive with millet and replace part of millet area, especially in the Agropastoral FS. Both feed and forage markets are expected to grow, hence the demand for quality forage will be strong. AS and PS, being stress tolerant (more drought-, heat- and poor soil-tolerant than maize, will continue to fit and be grown in the drier zones, where the dry season is often from 5 to 8 months depending on the farming system.

Cultivated sorghum, for which there are about 40,000 germplasm accessions, is generally perennial, resprouting tillers from stem crown buds after grain fill, if soil moisture is favorable. Sorghum has both vegetative and seed-based reproduction. The crown buds for tillering can commonly withstand 3 to 5 months dry conditions. **Long (6 to 8 month) dry season survival is key for SSA PS in many parts of current sorghum zones.** Such extended "dormancy" of crown buds **has not** been reported, but we found no evidence that the trait has been thoroughly screened. Experts contacted about such long dry season crown-bud survival supported our recommendation that it should be researched.

Several wild relatives of cultivated sorghum have sub-soil rhizomes extending out from the crown. These fleshy modified stems have buds for tillering. Such rhizomes, being protected under soil surface can withstand dry and cold stresses. They evolved for vegetative survival between favorable growing seasons. Though often difficult, it has been possible, through conventional wide-crossed plant breeding, to incorporate the rhizomatous trait into cultivated sorghum backgrounds. However, at this moment, no productive, tropically adapted rhizomatous diploids exist. Work is in progress, particularly at The Lands Institute in Kansas. In addition, research at the University of Georgia strongly supports the hypothesis that it will be possible to use molecular markers to identify progeny carrying the rhizomatous trait, even before flowering. This will be very helpful in accelerating breeding of improved rhizomatous perennial sorghum.

There are several potential biotic concerns related to developing rhizomatous cultivated perennial sorghum. First, is it not 100% sure that the rhizomes will stay viable for 8 months of dry season. Also important is the concern that PS plants could become weeds, spreading unwanted in fields, as does it's very weedy relative, Johnsongrass. Another significant biotic constraint for developing PS is prevalence of termites in the savannas of SSA. Savanna termites of SSA often cut and carry most of the dry vegetative matter underground in fields after harvest. They could jeopardize survivability of the dry season and ultimately the wide adoption of PS. Studies must be initiated to determine whether crowns with stay-green trait and/or metabolically active rhizomes would reduce termite damage. These studies could be conducted early on—even now in infested fields using Johnsongrass as a surrogate and cultivated sorghum with and without stay-green trait expressed in the crown. Chemical control of termites may be another option to enable vegetative survival over the dry season and that too can be explored.

It is envisaged that PS, capable of long dry season survival, will have at least one fodder cut (probably at about 5-weeks). Plants will then be left to produce grain toward the end of the rainy season, thus ensuring good grain quality for food or feed. One or possibly two fodder harvests, followed by a grain harvest, will be repeated each year until the PS crop is eventually rotated to other crops. This single grain crop per year approach will also avoid excessive damage from grain-feeding birds, *Quelea quelea,* in that damage from birds will be spread across all farmers' sorghum.

To ensure PS can be managed as above, keeping the short daylength photoperiod sensitivity of currently grown African sorghum is fundamental. The shortening daylengths, approaching the end of the rainy season, triggers flowering. This phenology, coupled with the trait of "long juvenile period", will contribute to wide adaptability across tropical daylengths. Experts interviewed believe this trait, widely used in tropical soybeans, also exists in sorghum and could be deployed.

It is recommended that several improved sorghum elite lines well-adapted to African savannas, and preferably already with the long juvenile trait, be used as recurrent parents for crossing with sources of the rhizomatous trait. Progeny intercrossing can then be initiated to incorporate many other essential agronomic and quality (grain and fodder) traits. The recurrent backcrossing strategy may include MAS backcross facilitation, reducing time and costs to develop high quality varieties carrying rhizomatous and stay-green traits. Survival of long dry season survival is the key to PS

If, for example, were weediness to appear in PS progenies and become an issue, further investment could be paused. This stepwise (stop-go) decision approach for financial support is recommended to donors who appreciate the potential benefits of African farmers having the choice of both annual and perennial sorghums for savanna farming systems with long dry seasons. We believe that if non-weedy rhizomatous PS can survive 6 to 8 months of dry-season, well-adapted varieties will likely be available for wide on-farm testing by mid-2030s and commercial seed multiplication soon thereafter. Demand for sorghum in SSA will be strong, especially for feed (grain and fodder). Having an extra option of PS will be very useful for farm families and ultimately for agro-industries in SSA. Figure 4.1 illustrates a stepwise (stop-go) approach to PS development and promotion.

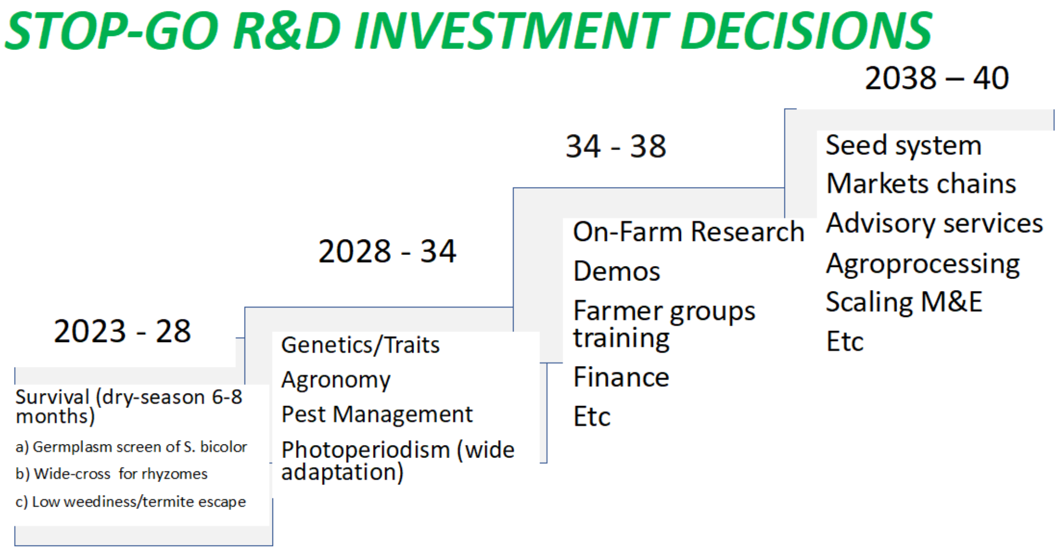


Figure 4.1. Stop-go investment trajectory for perennial sorghum development and promotion

In conclusion, the expansion of sorghums including potentially PS in SSA is almost certainly going to be a reality. As well as the standard advantages of the PS product profile enumerated above, there are possibilities for additional economically valuable traits to be incorporated into the PS product profile. For example, a perennial bio-energy sweet-sorghum, building on the recent breakthroughs at TAMU in the USA, would likely have enormous economic impact on farming communities in otherwise compromised districts not currently impacted by development opportunities. Naturally, support for well-targeted research on long dry-season tolerant PS and on bioenergy sweet PS would be mutually reinforcing thrusts.

4.2.3. Perennial rice potential

4.2.3.1 Introduction

4.2.3.1 PR in Farming Systems across SSA, SA and SEA

Under irrigated conditions in SSA SA and SEA, PR is well adapted and can be adopted now, but socio-economic factors, and environmental factors other than availability of water, will impact adoption. Where temperature and VPD are high, which will intensify under climate change, it is recommended that ponded water be maintained through sensitive stages from early boot to anthesis and grain set in each crop cycle, in order to maximize transpirational cooling of the canopy and especially the panicle (Pasuquin et al, CROPE). To enhance these benefits, PR should be back-crossed to cultivars with high yield potential, short stature, greater leaf area retention and lax panicle characteristics, in order to maximize stratification of canopy temperature and panicle shading (Pasuquin et al., CROPE). Nevertheless, crops of higher value than rice may be preferred under irrigated conditions, with annual crops preferred for greater system flexibility. Consequently, adoption of PR will remain relatively low (rising from about 2 to 10 % from 2030 to 2050) in irrigated areas and river deltas in SSA and elsewhere, in rice-wheat areas of SA, and in rice-rice areas of SEA. Where rice-rice is exclusive without other following crops, however, PR may have a place.

Where rainfed lowland conditions are favorable, in which ponded water depth remains shallow and risk of flood or drought is low, PR is again well adapted. These conditions arise in Maize Mixed and Cereal-Root Crop Mixed farming systems in SSA, along with Rice (Deltas) and Rainfed Mixed in SA, and Lowland Rice farming systems in SEA. In these systems, annual rice is important, as it can tolerate any waterlogging or short-term submergence (<3d) better than other crops, so annual rice dominates in the wet season, and where the wet season is long or bimodal, a second crop of annual rice may be grown. PR could replace some AR here, but not all, as post-rice crops such as pulses instead of a second rice crop are important for human nutrition and soil health in these areas. Where PR could have an advantage, however, is where the growing period is insufficient for two annual rice crops per year, or where the length of the growing period will decrease under climate change. In this situation, the ratoon crop offers the prospect of a shorter-duration second rice crop, which would also save labor, and improve soil health relative to double-rice cropping. There is also the prospect of using a self-regenerating annual legume or relay sowing after rice harvest for rotation and nutrition benefits, though the agronomy of this remains to be explored. Consequently, adoption of PR may commence at 5 % in 2030 rising to 15 % by 2050 in these conditions. If tolerances to short-term submergence and drought were to be added (see below), adoption could further increase to 25% by 2050.

Where depth and duration of ponded water in rainfed lowland is greater, current PR cultivars require back-crossing with a Sub-1 source for tolerance to short-term submergence of up to 14 days, which could be available in new PR cultivars by 2030. This applies to significant areas under Root-Tuber and some of Cereal Root Crop Mixed FSs in SSA, significant areas of Rice (Deltas) and some Rainfed Mixed in SA, and significant areas in SEA under Root-Tuber and some Lowland Rice. Addition of Sub1 would also secure significant areas of rainfed lowland against flooding damage, including the favorable areas of rainfed lowland in the previous paragraph. PR could also be back-crossed with FR13A for stem elongation under greater submergence, where water is deeper and especially longer in duration than 14 days. Inclusion of these genes, however, would not compensate for tidal saline, flash flood, turbid water, alkalinity or salinity, though these areas are smaller and of less significance. Rice already has an advantage in flood-prone due to aerenchyma, and the addition of submergence tolerance to PR should increase its adoption there substantially, as greater water availability and shorter dry season duration should favor PR survival and regrowth.

Under drought-prone rainfed lowland conditions, especially as the duration and severity of the dry season increases, performance and survival of PR will increasingly be challenged. Mild to moderate drought is expected to be significant in the drier areas under Maize Mixed and Cereal-Root Crop Mixed in SSA, Rainfed Mixed in SA and Lowland Rice in SEA, with some additional area in river deltas. Back-crossing of PR to well-adapted local cultivars should provide improved options for 2030, especially if crop cycle duration matches the length of the growing period, and target cultivars include current targeted genes for drought tolerance. Such cultivars and traits could further secure irrigated and favorable rainfed lowland as well. Associated agronomy should also assist, including use of direct seeding rather than transplanting to reduce root stress during soil transitions from anaerobic in puddled soils, so that soil structure is better maintained between hydrological states of anaerobic and aerobic soils under unpuddled conditions. Timely weed control prior to canopy closure and ponding of water by sufficient rainfall in bunded fields would be essential, as would timely N application to meet crop demand when ponded water is present.

Tolerance of PR to more severe water deficit, especially longer dry season duration, would require stronger perenniality and stronger drought tolerance, including bud dormancy for the dry period, survival of deep roots and crowns, rhizomes for more robust regrowth after the dry period, and selection for genomic hotspots for roots and grain yield under drought. Research is required to confirm that these traits contribute separately and in synchrony to greater drought tolerance, survival, regrowth and grain yield. Adoption of PR in mild to moderate drought should increase from 5 % in 2030 to 15 % in 2040, and even in severe drought if the combination of traits can be achieved.

Prospects for PR seem reasonable under favorable upland conditions in Highland-Mixed and Humid Lowland Tree-Crop FS in SSA, Highland Mixed in SA and Upland Extensive in SEA. Where dry seasons are short in duration (< 3 m) and temperatures in the highlands are not too low (> 13.5 C), PR should be biologically suited, with adoption dependent on the enterprise mix, compatibility, and demand for rice and other products. There are likely niches above 1700 m in Highland Mixed with adoption rising from perhaps 2 % in 2030 to 5 % in 2040. Greater adoption is likely as an intercrop between rows of trees under plantation agriculture in Humid Lowland Tree-Crop FS, with adoption rising from 5 to 20 % from 2030 to 2050.

Where water deficit is moderate to severe in the uplands such as the SSA Highland Mixed FS, with long dry seasons (> 6 months), adoption will be difficult unless all tolerances indicated for severe drought in rainfed lowland can be achieved in a PR cultivar. In the uplands, this is likely to be further exacerbated by difficult soils (shallow soils, low water-holding capacity, low fertility, acidic, hardpans) making survival a challenge. Nevertheless, it should be worth pursuing PR suitable for harsh rainfed lowland and rainfed upland conditions, to assist in stabilizing these fragile lands against absence of cover, overgrazing, leaching and soil erosion, as was originally envisaged for the development of perennial rice.

The target to develop a perennial rice to stabilize the sloping rainfed uplands should remain a consideration for the longer term, though it would be logical to progressively focus on shorter-term goals for PR under irrigated and favorable rainfed lowland, then short-term (< 14 d) submergence and mild to moderate drought, followed by moderate to severe drought, including the challenges of combined drought and heat stress under prolonged dry seasons (> 6 m), all of which will be further exacerbated by climate change. Impact of other limitations, as reviewed in sections 3.3 and 3.4, need to be monitored to determine if tolerance to tungro or rice blast, termites or birds needs to be added, perhaps with tolerance to longer-term submergence. Breeding and agronomy, supported by genetics, molecular biology, physiology, biochemistry, soil science, pathology and entomology will be essential to success in developing PR for the wide range of farming systems.

4.1.3 Potential Benefits

The potential benefits of having PR as an option include the prospect of an additional rice harvest wherever growing season duration exceeds the requirement for a single crop, but is insufficient for a second sown annual crop, or may become so as climate change makes seasonal conditions more variable and less reliable. PR should also have the advantage of assured re-establishment after commencement of seasonal rains which may become less reliable for seedling emergence. The increased yield over check varieties, shown in East and West Africa, and tolerance to some common diseases are important benefits in the case of SSA. In both SSA and Asia, PR also saves the crop establishment labor and net production costs in the second and subsequent years, taking into consideration any additional weeding costs and possibly irrigation costs where available to maintain PR viability over the dry seasons (Samson et al. 2018). Likewise, the established and deeper roots system should enhance reliability of yields as well as prospects of survival, especially if linked with axillary bud and shoot dormancy in the dry season, so no green bridge is present between crop cycles. Lack of cultivation will enhance soil health, and benefits of crop rotation could be retained if relay cropping, or self-regenerating annual legumes could be included following the rice crop. The strongest drivers of adoption are expected to be the increased yields and the labor and cost savings.

4.3. Recommendations

4.3.1 Recommendations related to farming systems for PS and PR

G1. PS and the Agropastoral Farming System. A high priority should be given to the SSA Agropastoral FS considering the climate change risk confronted by the agricultural population of over 100 million of whom more than half are severely undernourished and poor. Given the limited options for this extensive farming system and population and the threats of increased variability from climate change, it is recommended resources be focused on a risk reduction strategy through the development and scaling of PS to add resilience and diversity to the Agropastoral FS – using innovations which draw on GxExM synergies. The strategy would have to pay particular attention to the input and service value chains where risk is an impediment to investment. Scaling will need institutional innovations emphasizing community basedand flexible approaches to respond to climate signals. Successful climate resilient sustainable intensification and diversification of the Agropastoral FS would also reduce the need for humanitarian assistance and reduce the tendency for emigration to cities and beyond.

G2. PR and PS and the maize-based farming systems. Given the growing stress on SSA food systems from the surging population growth and increasing consumer incomes, agricultural intensification and diversification of the Maize Mixed FS and the Cereal Root Crop Mixed FS is urgent. This farm population of 140 m grow maize along with 4-5 other food and cash crops on 75 mha of cropland, including rainfed lowland rice, as well as irrigated rice in the scattered small scale irrigation farming. For these farming systems, the perennial grain components should be embedded into a system development or growth program. The scaling and further development of PR is a priority for these farming systems.

G3. Crop and whole farm simulation modelling. Such modelling is required to inform the management of climatic and market risk in leading SSA, and South Asian farming systems targeted for major investment in PS and PR. The modelling would estimate the contributions of PS and PR to the resilience and land and economic productivity of the target farming systems, refine the understanding of priority traits for crop improvement, explore GxM interactions, estimate the nitrogen and water use efficiencies, explore cropping patterns and rotations, assess feed and forage links for crop-livestock integration, etc.

G4. Climatic and market drivers of farming systems. Further analysis of the prospective changes in SSA farming systems during the coming decades until 2050 would be valuable information for agricultural research and development programs with a 20 year or more impact pathway.

G5. Drivers of scaling of PS and PR. Well performing PS or PR lines will not be automatically adopted by seed businesses or by smallholders. Targeted investment in innovative scaling strategies and programs are recommended. The persistence of large yield gaps for major crops in SSA and South Asia and the generally slow uptake of modern varieties and agronomy practices reinforces the urgent need for research into accelerating adoption and massive scaling of innovations including PS and PR and their complementary innovations.

G6. Social sciences will be critical throughout, not only to understand the preferences and adoption decision making processes of farmers, but also to monitor farmer acceptance and adoption and market changes.

4.3.2. Recommendations for Perennial Sorghum

Consider creating and enabling topic-oriented advisory groups to design required studies, with only judicious allocation of influence to any one institution. Partnerships and cooperation should “trump” competitive approaches. A critical mass of resources focused at the same location and same time frame should beget efficient progress on perennial systems developments.

PS1. Focus PS development primarily in existing sorghum growing zones in SSA requiring long (6 to 8 months) dry-season survival[7] of vegetative buds. There are two paths, namely:[8]

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[7] A robust, repeatable, low-cost protocol for identification of 6- 7- and 8-month dry-season survival must be developed early on.

[8] Characterization of the global sorghum germplasm for long dry-season vegetative survival has not occurred as far as we can ascertain. This work should be prioritized at the same time long dry-season survival of rhizomatous sorghum relatives takes place.

- Evaluate *S. bicolor* germplasm (there are circa 40,000 lines to test) for long dry-season survival, including for use as parental material and to understand mechanisms for non-rhizomatous dry-season survival.
- Create tropically adapted wide-cross originated rhizomatous progenies and test them for long dry-season survival.

PS2. Continue development of molecular screening tools such as MAS, especially targeting root-and- rhizome-linked traits, as well as physiologically complex traits such as drought and termite tolerance.

PS3. If germplasm capable of long dry-season survival is identified, begin experimentation of **tolerance to termite** attack of vegetative buds during the dry-season.

PS4. Conduct weediness studies of rhizome trait donors and then of progenies. Ensure that protocols (such as those of FAO) for experimentation with potential invasive species are applied to breeding materials with rhizomatous growth habit.

PS5. Consolidate desirable traits (see Table 2.1) in several intended recurrent parents that are to be used in the backcrossing program with a long dry-season-survival donor. This should include the long juvenile period trait or other mechanisms controlling flowering to match adaptation to production environments (daylengths) and coupling to wide short-day adaptation.

PS6. As soon as promising PS lines are available, begin active **PS oriented agronomic and pest management studies** to tune management toward optimization of performance and farm family incomes.

PS7. Initiate development of PS (perhaps non-rhizomatous) for situations where maize is no longer well adapted to increasingly dry environments, but not with critically long dry seasons such as in the sandy soils in the Cereal Root Crop Mixed FS.

PS8. Around 2030, or as soon as promising PS lines are available, **initiate perennial farming systems** studies, including integration with food and forage legumes, with attention to further optimization of crop/pasture/livestock integrated production systems.

PS9. Around 2030, as soon as promising PS lines are available, facilitate a **higher-level partnership of development institutions, governments, private enterprise and civil society** to map out strategy and policy toward scaling adoption and utilization of PS in SSA.

In conclusion, expansion of sorghums in SSA is almost certainly going to be a reality. Perennial sorghum will likely be a valuable technology.

4.3.2. Recommendations for Perennial Rice

PR1. Current cultivars of perennial rice should be promoted now for adoption under favorable conditions, where water deficit is mild, and flooding is limited to waterlogging of moderate depth without submergence.

PR2. Back-crossing PR to popular African cultivars such as Sahel-108 and WITA-9 should allow improved cultivars to be available by 2030. The range of PR could be further expanded by also backcrossing to include tolerance to short-term submergence (Sub1), aroma genes for improved grain quality, and flanking markers for genomic hotspots for root traits and yield under water deficit.

PR3. Longer-term crop improvement is needed to include traits for dry season survival, especially for long dry seasons exceeding 3 months in duration. This may include axillary bud dormancy, crown rhizome and root characteristics, and tissue osmotic characteristics for survival under these conditions.

PR4. The breeding efforts for severe water deficit and long dry-season survival must be supported by associated research to confirm traits and markers able to provide the desired plant characteristics as set out in section 3.4.1.

PR5. Associated systems considerations need to be addressed throughout, including agronomy, longevity, weed control, PR removal when desired, rotation or relay with associated legumes or brassicas, and assessment of forage contributions as well as grain yield.

PR6. Mechanized dry direct seeding, drilled fertilizer at sowing (topdressing later) and timely weed control should receive special attention to benefit soil conditions for PR regrowth and for subsequent establishment and growth of non-rice relay or rotation crops.

PR7. The role of rhizomes, including short rhizomes, in both dry season survival and weed potential, must be assessed, along with requirements to remove PR when desired.

PR8. As PR expands in area, and especially where the growing season is extended to allow an additional ratoon harvest beyond that available with annual rice, there may be a need to address **rats, termites or birds,** as discussed in section 3.4.5.

PR9. While grain quality of current PR is considered acceptable, it is not premium, so breeding should **target aroma and other desired characteristics to improve milling, cooking and eating preferences**. This should also impact market price, even under irrigated systems against higher-valued crops.

ANNEX 1

Supplementary Notes on Target Farming Systems 2030-2050

Three regions are considered in this analysis, for which some key characteristics are presented in Table A1.

Table A1. Land and population, 2020

Land	SSA	SA	SEA
Land area	2,413	439	501
Human-induced degradation, 2015	14%	41%	24%
Cultivated land/cap, 2017	0.95	0.17	0.21

Sources: FAOStAT, FAO 2021a,

Historical data analysis, focused on monthly precipitation and max and min temperatures from the period 1979-2021 (and partially 2022) was particularly useful for the analysis of the PR trials during 2018-2019 at 11 locations in Uganda. They provided some indications of historical climate in some other locations in Africa. It was possible to extract data for the Maize Mixed FS but not the Agropastoral FS because the latter contained areas with contrasting seasonal precipitation and temperature patterns from west to east SSA, and to southern SSA. Time did not permit the extraction of daily data to estimate the drought and crop failure risk during the planting season.

Before looking at the principal farming systems of SSA, it is worth considering the dynamics of land use and roles of the major food grains over the past 60 years in different regions of SSA. Of the 193 mha of land in Africa (SSA plus North Africa) under temporary (annual) crops in 2020, maize was harvested from 43 mha, sorghum from 27 mha, rice from 17 mha, millet from 19 mha and wheat from 10 mha. In relation to other food crops, cassava occupies 22 mha, yams 9 mha, sweet potatoes 4 mha and plantains 5 mha. Legumes and oilseeds include groundnuts (17 mha), cowpeas (15 mha), sesame (9.7 mha), beans (8.5 mha) and soybeans (2.6 mha). The changes in area and yield of the three principal staple grains sorghum, rice and maize in the major African regions, South Asia and South-East Asia are listed in the following table A1.

Table A2. Historical African areas and yields of major food grains

Region	Yr	Sorg A Mha	Sorg Y t/ha	Rice A Mha	Rice Y t/ha	Maize A mha	Maize Y t/ya
Africa	1961	13.2	0.81	2.8	1.55	15.5	1.04
	1980	14.1	0.92	4.7	1.83	18.1	1.56
	2000	21.2	0.87	7.6	2.31	24.2	1.81
	2020	27.3	1.01	17.2	2.21	43.1	2.10
East Africa	1961	2.6	0.75	1.0	1.72	5.7	1.01
	1980	3.3	1.02	1.6	1.61	7.7	1.26
	2000	3.4	0.86	2.0	1.90	10.1	1.48
	2020	5.0	1.60	3.9	2.54	17.1	2.01
Middle Africa	1961	1.0	0.69	0.2	0.88	1.6	0.75
	1980	1.0	0.67	0.4	0.93	2.0	0.73
	2000	1.1	0.80	0.6	0.90	2.7	0.94
	2020	2.2	1.04	1.8	1.12	6.6	1.08

Southern Africa	1961	0.6	0.76	0.0	1.90	4.3	1.25
	1980	0.5	1.66	0.0	2.50	4.8	2.34
	2000	0.3	1.98	0.0	2.34	4.4	2.68
	2020	0.1	2.03	0.0	2.92	2.9	5.40
West Africa	1961	7.2	0.75	1.4	0.93	2.7	0.74
	1980	6.2	0.87	2.3	1.42	2.3	0.93
	2000	12.1	0.88	4.3	1.65	6.0	1.35
	2020	14.0	0.97	10.9	1.92	15.0	1.73

Source FAOSTAT

Two centuries ago sorghum was the traditional food grain of Africa, supplemented by millet and tubers such as yams. In contrast to the USA and Asia, the area of sorghum in Africa has doubled since 1961, and over the past 20 years has expanded by 30% to 27.3 mha across Africa, by 46% in East Africa and doubled in Middle Africa. As illustrated in Figure A1, the major sorghum growing countries are Nigeria (5.2 m ha), Sudan (5.8 mha), Niger (3.7 mha), Burkina Faso (1.9 mha), Ethiopia (1.8 mha) and Mali (1.8 mha). National average yields vary considerably from 2.8 t/ha in Ethiopia to 1.2 t/ha in Nigeria and 0.58 t/ha in Niger.

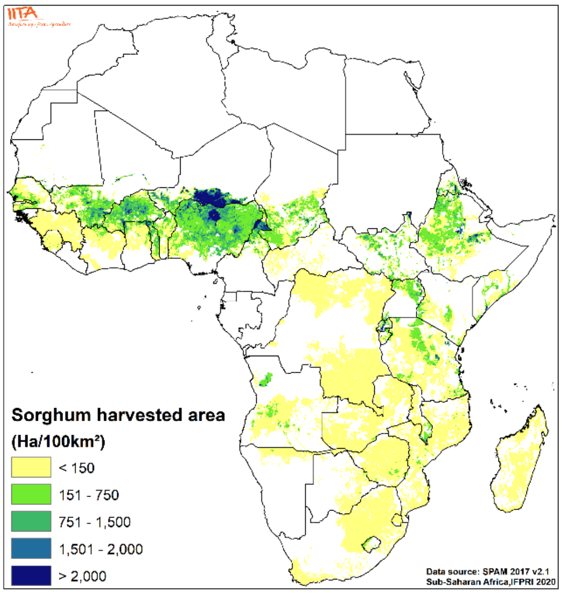

Figure A1.1. Distribution of sorghum in SSA

West Africa contains two-thirds of rice area in SSA, as shown in Figure A1.2.

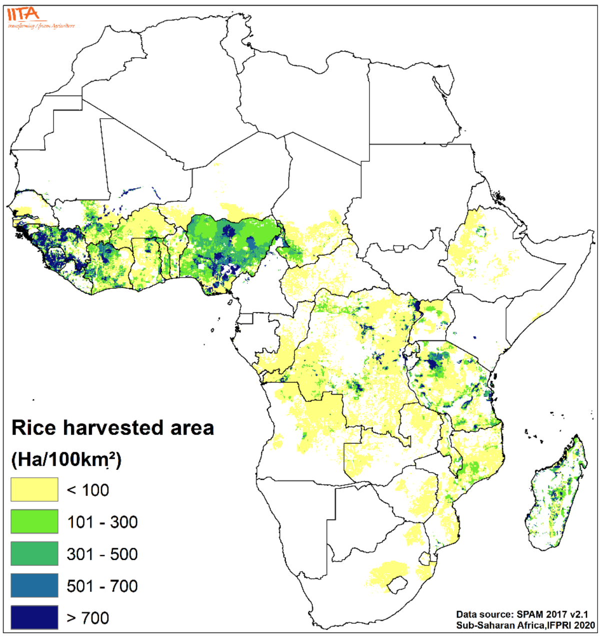

Figure A1.2. Distribution of rice in SSA

Table A3. Historical South and SE Asian areas and yields of major food grains

Region	Yr	Sorg A mha	Sorg Y t/ha	Rice A Mha	Rice Y t/ha	Maize A mha	Maize Y t/ya
S Asia	1961	18.8	0.44	46.5	1.58	46.5	0.90
	1980	16.2	0.66	55.2	2.03	55.2	1.35
	2000	10.2	0.76	61.0	2.98	61.0	2.57
	2020	Tba	0.86	62.9	4.05	62.9	4.66
SE Asia	1961	0.01	2.44	28.5	1.62	28.5	1.36
	1980	0.24	1.05	35.0	2.42	35.0	2.02
	2000	0.34	0.93	43.0	3.53	43.0	3.34
	2020	0.16	1.08	44.1	4.29	44.1	7.83

One element of data analysis was future climates for 2030, 2040 and 2050, in order to judge the probability of adoption of PR or PS, the influence on the farming system cropping pattern and livestock husbandry, and the benefits from adoption. FAO GAEZ ver 4 website contained climatic data modelled by IIASA for FAO for the period up until 2050. Unfortunately FAO had not received the supporting monthly data which could illustrate shifts of seasonal cropping patterns. The data base had an anomalous data point in 2037.

Table A1.4: PS & PR South Asian Farming Systems fit

Farming Systems	Land area (% of region)	Agric Popn[9] (% of region)	Principal Livelihoods, crops, livestock	Perennial rice (current) system fit (0-10)	Perennial rice (post 2030) system fit (0-10)	Perennial sorghum (post 2030) system fit (0-10)
Rice	7	17	Wetland rice (both seasons), vegetables, legumes, off-farm activities 2 depths flood prone Submergence	B: Rf lowland 9 S: 8	B: 10 (if elongation) :S: 10	S: 2
Coastal Artisanal Fishing	1	2	Fishing, coconuts, rice, legumes, livestock	S: 3	S: 4	S 2
Rice-Wheat	19	33	Irrigated Rice, wheat, vegetables, livestock including dairy, off-farm activities	B: 8 S: 7	B: 9 S: :7	B: 6 S: 3
Highland Mixed	12	7	Cereals, livestock, horticulture, seasonal migration	S: 6 (labor constraints) (potential slope control)	: S: 6 (drought prone) (FS: rainfed 7, after backcross)	B:8 FS: 3:
Rainfed Mixed	29	30	Cereals, legumes, fodder crops, livestock, off-farm activities	B: high S: 5-7 (in good rainfed lowland, or irrigated) S: 5 (rainfed lowland PR	B: high S: 7 Backcrossed for frought	B: 8 FS: 6-7
Dry Rainfed	4	4	Coarse cereals, irrigated cereals,			FS: 7-8

			legumes, off-farm activities	FS: 3 (for irrigated)	FS: 3 (for irrigated)	
Pastoral	11	3	Livestock, irrigated cropping, migration	B: 6-8 FS 0 in rainfed (4 in patches)	B: 6-8 FS 0 in rainfed (5 in patches)	Millet land FS: 3
Sparse (arid)	11	1	Livestock where seasonal moisture permits	FS 1-2	FS 1-2	FS 1-2
Sparse (mountain)	7	0.4	Summer grazing of livestock	FS 0	FS 0	FS 1 for forage (if cold tolerant)
Tree Crop	little, dispersed	1	Export or agro-industrial crops, cereals, wage labor	FS 1	FS 1	FS 0
Urban Based	<1	1	Horticulture, dairying, poultry, other activities	FS 0	FS 0	FS 0

Source: Table 5.1, Dixon et al 2001, p. 174

Table A1.5: PS & PR South-east Asian Farming Systems fit

Farming Systems	Land area / Agric populat'n (% of region)		Principal Livelihoods, crops, livestock	Perennial rice (current) system fit (0-10)	Perennial rice (post 2030) system fit (0-10)	Perennial sorghum (post 2030) system fit (0-10)
Lowland Rice	12	42	Rice, maize, pulses, sugarcane, oil seeds, vegetables, livestock, aquaculture	FS 6 irrigated > harsh rainfed lowland	FS 8	FS 2
Tree crop mixed	5	3	Rubber, oil palm, coconuts, coffee, tea, cocoa, spices, rice, livestock	Inter trees FS 3	Inter trees, backcrossing FS 6	FS 3-4 (forage, ? sweet forage)
Upland intensive mixed	19	27	Rice, pulses, maize, sugarcane, oil seeds, fruits, vegetables, livestock	FS 4 stabilize soil, save labor	FS 7 stabilize soil, save labor with selection and backcrossing by 2040	FS 5 (forage for local livestock, grain for poultry feed market ? fish)

Highland extensive mixed	5	4	Upland rice, pulses, maize, oil seeds, fruits, forest products, livestock	FS 3 in lower latitude	FS 6 (with backcrossing)	FS 3 (cooler, drier, lower for forage, also further from poultry feed markets)
Temperate mixed	6	14	Wheat, maize, pulses, oil crops, livestock	FS 0	FS 0	FS 2
Pastoral	20	4	Livestock with irrigated crops in local suitable areas	FS 0	FS 0	FS 0
Root-tuber	2	<1	Root crops (yam, taro, sweet potato), vegetables, fruits, livestock (pigs and cattle)	B: 7 FS 5	B 8 FS 6	B 7 FS 3
Sparse (forest)	10	1	Hunting, gathering	FS 0	FS 0	FS 0
Sparse (arid)	20	2	Local grazing where water available	FS 0	FS 0	FS 0
Urban based	<1	1	Horticulture, dairy, poultry	FS 0	FS 0	FS 0
Coastal artisanal fishing	1	2	Fishing, coconut, mixed cropping	B medium FS 0	B medium FS 0	B medium FS 0

Source: Table 6.1, Dixon et al 2001, p 22

ANNEX A2

Supplementary notes on perennial sorghum

A 2.1. Leading research groups, capacities, strategies

We believe much can be realized in sorghum enhancement for SSA by coupling reliable resources to a coordinated initiative with shared vision. It is logical to not have a stand-alone initiative on PS, but to have PS be part of a full-throated development program that would likely include AS, PS and bioenergy sweet sorghums. The work should cover varietal development, agronomy and socioeconomics. The roles of public and private sector partners should be encouraged. Such an alliance requires careful planning and operational capacities. Competitive approaches should be rejected.

Given the recent CGIAR reorganization in which CIMMYT has been asked to provide leadership on Sorghum improvement for SSA, CIMMYT will be a key and lead institution for implementation of PS R4D.

NARS of Mali, Burkina Faso, Ghana, Nigeria and Senegal will be among the likely partners from West Africa. There may be useful facilities at IITA new station for the Guinea Savanna at Bamako Mali where ICRISAT has been working for many years. In Eastern and Southern Africa NARS of Ethiopia, Uganda, Tanzania, Zambia and Zimbabwe would be among logical partners. Involvement by universities in Developed countries will be important including for molecular genetics support and screening 40K lines of sorghum for long dry season survival. Examples might include University of Queensland, Purdue University, Texas A&M, University of Georgia, Cornell, Kansas State University, etc. The Lands Institute, based in Kansas, has been investigating PS for years and has obvious experience to share.

A 2.2. Sorghum Breeding/Genetics

This section is not intended to be a coherent review of relevant genetics for the creation of PS. In this annex are nuggets of information that complement the breeding and genetics notes in Chapter2. Notes on making wide crosses in Sorghum are primarily extracted from Rakshit 2016.

Analysis of meiosis of S. bicolor ⍰ S. halepense hybrids proved that S. halepense possesses one genome similar to S. bicolor, and another divergent or a rearranged genome. This suggests that S. halepense is an allopolyploid or segmental allopolyploid (Duarra and Stebbins 1952; Tang and Liang 1988). The hexaploid species, S. halepense and S. sudanense, possessed comparable chromosome architecture

Ng'uni et al. (2010) clearly demonstrated that classifying Australian species S. macrospermum and S. laxiflorum as a separate section was not well supported. They further found that S. almum was closely associated with S. bicolor, suggesting the latter to be the maternal parent of the former.

All the reports on molecular phylogeny of sorghum are in agreement that there are two well-supported major clades within sorghum (Kellogg 2013). S. bicolor and its close relatives, S. halepense, S. propinquum, S. arundinaceum, S. almum, and S. drummondii are represented in clade 1. Except S. propinquum, which is Asian, all are of African origin.

Based on the extent of crossability of the wild species with a cultivated gene pool, wild species are classified into three gene pools: (i) cross-compatible wild species that produce fertile F_1 plants categorized into the primary gene pool; (ii) the secondary gene pool consisting of distant wild species that produce partially sterile hybrids; and (iii) the tertiary gene pool consisting of far distant wild species that have difficulty producing F_1 hybrids (Harlan and de Wet 1972). The primary gene pool contains all three subspecies of S. bicolor: subsp. arundicum, bicolor, and drumondii (Cox 1983; de Wet et al. 1976). The two species in Eusorghum, S. propinquum and S. halepense, constitute the secondary gene pool. Sorghum bicolor and S. propinquum crosses are easily made, in which the meiosis is normal, and progeny are fertile. However, there has been negligible use of this germplasm in applied sorghum improvement (Wooten 2001). Sorghum and S. halepense hybrids are possible with difficulty. Major efforts to utilize S. halepense are directed towards developing perennial grain crops (Piper and Kulakow 1994; Cox et al. 2002; Dweikat 2005).

The tertiary gene pool contains the remaining 17 species within the four other sections. Most of the desirable traits for cultivated sorghum are contained in the tertiary gene pool (Harlan 1965), but this gene pool has remained more or less inaccessible as successful hybrids could not be recovered despite numerous efforts (Kuhlman et al. 2010).

As early as 1967, Magoon et al. observed irregular chromosome pairing in the two inter- specific hybrids between the nonrhizomatous sub- sect, Arundinacea, the S. propinquum and rhizomatous subsect, Halepensia species, based on which they suggested alienating S. propinquum from the subsect Arundnacea. Other taxa of sorghum were crossable with cultivated types leading to formation of different races. Introgression of genes from arundinaceum into the early cultivated types produced the guinea phenotype and permit- ted extension of grain sorghum cultivation into forest areas (de Wet et al. 1976). Race virgatum crosses with durra sorghums; race verticilliflorum is widespread and crosses with cultivated types; and race aethiopicum crosses with cultivated races caudatum and durra. S. halepense or Johnsongrass, is one among 10 worst weeds of the world but it has tremendous vigor and adaptation.

Hodnett et al. (2005) determined that pollen–pistil incompatibilities are the main cause of reproductive isolation between sorghum and the tertiary gene pool. Incompatible reaction leading to no pollen tube growth of wild species in the stigma and style leads to unsuccessful fertilization (Dhillon et al. 2007a, b). The authors demonstrated that the recessive iap allele circumvents pollen–pistil incompatibilities and permits hybrids to be made between S. bicolor and species of the tertiary gene pool. Using this allele, hybrids were obtained between S. bicolor and S. macrospermum (Price et al. 2005a)

Going Forward on Wide crosses: Undomesticated wild species of sorghum are found to be the repository for resistance to biotic and abiotic stresses and these are underexploited in sorghum breeding programs. Breaking the pre-fertilization barriers introducing the wild traits through backcrossing can open a new avenue to increasing sorghum production with the genome sequence available in sorghum, and a large number of genotypes being re-sequenced, it is high time that promising wild species with proven traits of importance are to be sequenced so that genes or alleles can be discovered and deployed in breeding programs. With the advent of molecular genomics, conventional cytogenetic tools might have become redundant but are needed to bring together the plethora of cyto- logical information generated over this period with the genomic information being generated at a rapid pace. Hari D. Upadhyaya, Mani Vetriventhanand Santosh Deshpande In Rakshit, 2016.

Root traits for drought tolerance and dry-season survival (perennialization)

Ali et al. (2009) investigated the genotypic variation for root traits in local landraces of Pakistani origin and observed considerable genetic variation for dry root weight, which is an important determinant of drought tolerance in sorghum. Many studies have identified dry root weight and root length density (RLD) as reliable and easiest root components to determine the drought tolerance in sorghum (Nour et al. 1978; Matsuura et al. 1996; Ali et al. 2009). See D. Joshi in Rakshit 2016

Apart from these components, spatial distribution of roots and rooting depth are the critical factors for determining the drought-tolerance potential and survival of plants in drought-prone environments. The importance of spatial distribution of roots and rooting depth for crop productivity arises from the fact that soil resources are haphazardly distributed in time and space and are subjected to localized depletion in stress environments (Robinson 1994). This is especially important in crops such as sorghum, as they are frequently grown in moisture-limited environments. Root growth angle is an important determinant of RSA that strongly influences the spatial distribution and rooting depth in sorghum. In fact, the root angle spread at an early growth stage can serve as a useful predictor of the distribution and root biomass at the adult stage (Singh 2010) and may serve as a good reference point for comparison to other environmental conditions. Studies have demonstrated that the vertical distribution pattern of roots as a consequence of narrow root angle enhances the rooting depth, which is important if water availability in the upper soil layers becomes insufficient in terminal drought-stress environments (Manschandi et al. 2008; Hammer et al. 2009; Uga et al. 2011). On the other hand, wide root angle, which results in more horizontally distributed and shallow

Anatomical traits, root cortical aerenchyma (RCA), cortical cell file number (CCFN), and cortical cell size (CCS), were reported to reduce the metabolic cost of root growth in maize under moisture and nutrient-limited environments (Lynch 2015). Zhu et al. (2010) compared maize recombinant inbred lines (RILs) differing for RCA formation under moisture stress in the field and soil mesocosms in greenhouse. In field conditions, lines with high RCA had high RLD and produced 30 % more shoot biomass at flowering compared with the lines with low RCA. On average, high RCA lines yielded eight times more than low RCA lines. In mesocosms, high RCA lines were characterized by less seminal root respiration, deeper rooting, and greater shoot biomass compared with low RCA lines. These findings suggested that RCA deserves consideration as an important component of RSA to improve drought tolerance in cereal breeding programs. Therefore, there is an urgent need to explore the genetic basis and functional aspects of root anatomical traits in sorghum. Identification of genomic regions governing root anatomical traits would greatly facilitate their use in sorghum breeding programs.

Singh et al. (2011) assessed the inheritance pattern of nodal root angle and dry root weight in a set of 44 inbred lines and 30 hybrids. It was observed that both traits were polygenically controlled and exhibited moderate heritability. Although the heritability of nodal root angle was moderate, its genetic architecture was not simple, as illustrated by the significant specific combining ability (SCA) effects and the high contribution of male and female interactions to the heritability.

In addition to this, imprecise QTL identification, inconsistency in validation of QTLs detected in controlled and field conditions, their unstable expression across the populations and environments, and unfavorable epistatic interaction have adversely affected the breeding programs entailing manipulation of RSA through MAS. For these reasons, there have been very few reports on the use of MAS for improvement of RSA in cereal breeding programs and there is no report on marker-assisted introgression of QTLs governing superior root characters to drought-susceptible genotypes in sorghum.

However, a challenging obstacle to the deployment of these RSA components in sorghum breeding is the difficulty in evaluating root phenotypes of a large number of breeding lines or multiparental mapping populations. Therefore, efforts should be directed towards development of robust root screening platforms that are capable of (i) expressing high heritability for the measured component trait, (ii) minimizing the G ▯ E interaction, (iii) screening the root trait at the early seedling stage to shorten the selection cycle and speed up genetic improvement, and (iv) finally, establishing the genetic correlation between the root trait phenotyped on the platform and ultimate breeding objective.

Immediate attention needs to be paid towards identification of genomic regions governing root anatomical phenes, which will greatly facilitate their use in breeding programs.

Meta–QTL analysis followed by cloning of QTLs, which are stable across populations and environments, will provide a driving force in molecular breeding for RSA because a cloned QTL can offer a reliable marker for MABC. However, the impact of a cloned QTL or candidate gene underlying the QTL region on plant productivity needs to be tested in a given environment. Furthermore, transformation of the knowledge acquired from genomics-oriented approaches into a drought-tolerant high-yielding cultivar wit

Therefore, an exhaustive characterization of diverse germplasm sources, namely core collections, diversity panels, multiparental breeding populations, and landraces, is required for identification of appropriate donors for superior root traits. In addition to the mainstream gene pool, wild species can serve as potential donors for the root traits due to their ability to colonize a wide range of moisture and soil regimes and to with- stand harsh and nutrient-limited environments. Potential donors for root traits have been observed in wild species of barley (Grando and Ceccarelli 1995), rice (Liu et al. 2004), and wheat (Reynold et al. 2007; Placido et al. 2013). However, wild sorghum species are still unexplored for root traits. Utility of RSA components such as nodal root angle, dry root weight, and RLD is fairly well established to influence drought tolerance in sorghum. In addition to this, traits such as nodal root angle at the early seed- ling stage have been suggested as proxy traits to determine drought tolerance of adult sorghum plants. However, a challenging obstacle to the deployment of these RSA components in sorghum breeding is the difficulty in evaluating root phenotypes of a large number of breeding lines or multiparental mapping populations. Therefore, efforts should be directed towards development of robust root screening platforms that are capable of (i) expressing high heritability for the measured component trait, (ii) minimizing the G X E interaction, (iii) screening the root trait at the early seedling stage to shorten the selection cycle and speed up genetic improvement, and (iv) finally, establishing the genetic correlation between the root trait phenotyped on the platform and ultimate breeding objective.

QTLs have been identified for traits related to root morphology, which has resulted in a great magnitude of knowledge and better understanding of the genetic control of RSA in sorghum. However, the root anatomy of sorghum is very poorly understood at present. Therefore, immediate attention needs to be paid towards identification of genomic regions governing root anatomical phenes, which will greatly facilitate their use in breeding programs. Meta–QTL analysis followed by cloning of QTLs, which are stable across populations and environments, will provide a driving force in molecular breeding for RSA because a cloned QTL can offer a reliable marker for MABC. However, the impact of a cloned QTL or candidate gene underlying the QTL region on plant productivity needs to be tested in a given environment. Furthermore, transformation of the knowledge acquired from genomics-oriented approaches into a drought-tolerant high-yielding cultivar with improved RSA is the most daunting challenge faced by breeders.

Efforts should also be directed towards understanding the physiological mechanisms that control functional aspects of RSA and its impact on crop performance in the field. Understanding the physiological mechanism and signaling behavior of roots in response to stress and sub- sequent physiological alterations in shoots will certainly assist plant breeding efforts towards RSA improvement in sorghum. Indeed, a multi- disciplinary approach is required to integrate growing omics techniques with plant physiology, agronomy, and breeding to improve productivity of sorghum under drought through genetic manipulation of RSA.

Transformation technology. Sorghum is an important cereal crop and has been grown in a wide range of environments from tropic to warm-temperate zones. Genetic improvement of this crop has been based on those traditional breeding methods, but there is a limited application of genetic transformation for sorghum improvement due to its recalcitrance to genetic manipulation in vitro. The current study aimed at development of immature inflorescences as a genetic transformation system for sorghum. Immature inflorescences of two sorghum elite lines were chosen as the explants for developing a new method for genetic transformation. Sorghum immature inflorescences were collected from plants at the flowering stage and co-cultured with virulent *Agrobacterium tumefaciens* strain LBA4404 containing one of the special gene constructs. Once co-cultivation was completed, the treated immature inflorescences were moved onto regeneration medium to induce development of shoot and root from the resulted embryogenic callus. This system was also amenable for the microprojectile bombardment (biolistic particle delivery system) method. Putatively transgenic plants were confirmed for the presence of transgene in the plants based on the molecular analysis of the T_1 plants. All resulted transgenic plants were normal in morphology and fully fertile. The transformation system developed with the immature inflorescence is a simple and efficient method for sorghum transformation, which can speed up the process of engineering new varieties.

ANNEX 3

Supplementary notes on Perennial Rice – Uganda

PLEASE NOTE: This Appendix is NOT FOR PUBLICATION. The data belong to Dr Jimmy Lamo from NARO Uganda, who intends to publish the data shortly in the international scientific journal, Crop and Environment. The information below is provided to support text regarding the Uganda data in the main report. Please respect these data by citing the scientific paper as the source of evidence.

Eleven rice genotypes were compared over 11 locations in Uganda between 2017 and 2020. At ten sites, crops were sown in 2018 and ratooned in 2019, except at Wakiso, which was sown in 2017 and ratooned in 2018, 2019 and 2020. The locations were Wakiso, Oyam, Kasese, Bugiri, Lira, Soroti, Alebtong, Gulu, Nwoya, Pakwach, Butaleja, which provided 26 site-season-year combinations (Environments E; Table 1). At each site, a randomized complete blocks design was used, comprising 11 genotypes (G) with 3 replicates. The genotypes were TXD306, MET20, PR107, ARU1189, IR1052, MET12, AGRA78, MET16, AGRA55, KOMBAKA and WITA-9. Days to flowering (DTF), days to maturity (MTY), plant height (PHT), tiller number (TNO), disease rankings (0-9) for rice blast (BLAST), bacterial leaf blight (BLB), bacterial leaf streak (BLS), brown leaf spot (SPOT), rice yellow mottle virus (RYMV), and grain yield (YIELD) were recorded. For further details, see Lamo et al forthcoming (Crop and Environment).

Table A3.1. Means for 10 traits across 5 Environment (E) groups and 3 Genotype (G) groups and means for 5 traits in 3G x 5E groups, for rice in Uganda. The traits were Days to flowering (DTF), Days to maturity (MTY), Plant height (PHT), Tiller number (TNO), Disease rankings for Rice blast (BLAST), Bacterial leaf blight (BLB), Bacterial leaf streak (BLS), Brown leaf spot (SPOT), Rice yellow mottle virus (RYMV), and Grain yield (YIELD). Environment groups were Kasese (E1); Pakwash (E2); Soroti (E3); Wakiso, Oyam, Butaleja, Alebtong, Gulu, Nwoya (E4), and Buguri and Lira (E5). Genotype groups were PR107, ARU1189, MET12 (G1); MET20, IR1052, MET16, AGRA55, KOMBAKA, WITA-9 (G2); TXD306, AGRA78 (G3).

MEANS	DTF	MTY	PHT	TNO	BLAST	BLB	BLS	SPOT	RYMV	YIELD
E1	98	123	99	12.1	1.5	0.9	0.09	2.7	0.29	3.86
E2	96	121	96	12.3	1.4	1.2	0.10	2.4	0.44	4.99
E3	97	122	97	12.2	1.4	0.9	0.09	2.8	0.56	4.98
E4	98	122	98	12.5	1.4	1.0	0.07	2.7	0.34	4.90
E5	100	122	99	12.2	1.4	0.9	0.07	2.6	0.28	5.43
G1	90	114	97	12.8	1.2	0.9	0.05	2.2	0.05	6.07
G2	98	122	98	11.9	1.2	1.1	0.11	2.7	0.46	4.64
G3	108	131	99	12.8	2.3	0.7	0.02	3.4	0.64	4.18
Mean										4.96

YIELD	E1	E2	E3	E4	E5	Mean
G1	4.79	6.26	6.07	6.04	6.53	5.94
G2	3.46	4.59	4.76	4.56	5.19	4.51
G3	3.65	4.28	4.02	4.18	4.49	4.15
Mean	3.97	5.04	4.95	4.93	5.40	4.96

DTF	E1	E2	E3	E4	E5	Mean
G1	90	88	90	90	91	90
G2	99	96	98	98	100	98

G3	108	106	109	108	110	108
Mean	99	97	99	99	101	99

RYMV	E1	E2	E3	E4	E5	Mean
G1	0.00	0.15	0.04	0.06	0.00	0.05
G2	0.06	0.72	0.74	0.37	0.39	0.46
G3	1.42	0.06	0.80	0.70	0.40	0.67
Mean	0.49	0.31	0.53	0.38	0.26	0.39

BLAST	E1	E2	E3	E4	E5	Mean
G1	1.44	1.22	1.22	1.24	1.18	1.26
G2	1.22	1.30	1.18	1.21	1.09	1.20
G3	2.33	2.11	2.40	2.24	2.47	2.31
Mean	1.67	1.54	1.60	1.57	1.58	1.59

SPOT	E1	E2	E3	E4	E5	Mean
G1	2.11	1.85	2.40	2.17	2.36	2.18
G2	2.78	2.37	2.78	2.64	2.71	2.65
G3	3.33	3.22	3.52	3.45	3.60	3.43
Mean	2.74	2.48	2.90	2.75	2.85	2.75

Notes: Environment groups were Kasese (E1); Pakwash (E2); Soroti (E3); Wakiso, Oyam, Butaleja, Alebtong, Gulu, Nwoya (E4), and Buguri and Lira (E5). Genotype groups were PR107, ARU1189, MET12 (G1); MET20, IR1052, MET16, AGRA55, KOMBAKA, WITA-9 (G2); TXD306, AGRA78 (G3).

Perennial rice PR107 averaged 5.90 t ha^{-1} to annual check WITA-9 averaging 4.80 t ha^{-1}, for a 22.5% yield increase over first and second seasons. This was under favorable rainfed lowland conditions, mainly in north, mid-north and central Uganda, and mostly around 1000 m in altitude (980-1115 m) – see Table 2 for site characteristics. There was a lower percent increase in some higher-yielding sites in the east, while the largest was 50% at a lower-altitude site (E2, Pakwash, 650 m), where flooding may occur. This area in Uganda is Maize Mixed, favorable rainfed, with a short (3 m) “dry” season with monthly approximate average rainfalls of 25-75 mm depending on the site. Although yields were lower in Kasese (E1) at higher altitude, there may be potential for spillover into the Highland Perennial system. Rice yellow mottle virus (RYMV) resistance of PR107 was a huge plus, as the reference eating-quality cultivar Supa from Tanzania is now susceptible to RYMV, blast and sheath blight, the 3 major diseases of rice in SSA. PR107 had resistance to all 3 diseases and had better eating quality than the preferred local check, WITA-9. All 3 genotypes (PR107 and annuals ARU1189 and MET12) in group G1 were shorter in duration with resistance to all diseases. Clearly, perennial rice does well in favorable rainfed lowland conditions with short dry seasons. PR107 has now been released to farmers in Uganda.

Table A3.2: Site characteristics (favorable rainfed lowland)

	Location	Altitude masl	Soil (%)	Av ann rainfall Mm	LGP ??? Where	Months > 100 mm	Dry season c.av.mm monthly	PR107 yields t/ha	WITA-9 Yields t/ha	
Lira		1061	Ferral 78 Alisol 22	1341		7 cont, 4>150mm	25,20,25	6.4	5.0	
Gulu	Gulu District, N Region, 2 deg N	1057	Alfisol 56 Ferral 44	1470		7 cont, 6> 150 mm	25,10,20	5.9	4.5	

Nwoya	Nwoya District, Acholi, N Region, nr Gulu	982	Alisol 100	1314				5.6	4.5	
Pakwach	Pakwach District, N Region, N of L. Albert	652	Lepto 67 Ferral 33	1053		2+4, 0>150mm	25,15,20	5.9	3.8	
Oyam	Oyam District, Central Region	1110	Ferral 66 Gleyo 17	1277				5.6	4.5	
Soroti	Soroti District, Teso Region	1173	Ferral 67 Plinth 22	1327		7 cont, 3>150mm	30,25,30	6.4	5.3	
Buleja	Butaleja District, E region, nr Mbala	1066	Plinth 78 Fluvi 22	1227		3+4, 2> 150mm	70,50,60	6.0	5.3	
Bugiri	Bugiri District, E Region	1076	Ferral 44 Plinth 44	1365				6.9	5.5	
Kasese	Kasese District, W Region, N of L. George	1057	Fluvi 67 Phaeo 22	1061		3+4, 2>150mm	90,65,80	4.6	3.5	
Wakiso	Wakiso District, next to Kampala	1114	Nitisol 100	1232		3+3, 1> 150mm	80,60,70	5.5	4.4	
Alebtong		1058	Fluvi 67 Ferral 33	1297				5.5	4.4	

ANNEX 4

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ANNEX 5

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