Chapter 11
Toolbox for Working with Root, Tuber, and Banana Seed Systems

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Abstract Root, tuber, and banana (RT&B) crops are critical for global food security. They are vegetatively propagated crops (VPCs) sharing common features: low reproductive rates, bulky planting materials, and vulnerability to accumulating and

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spreading pathogens and pests through seed. These crops are difficult to breed, so new varieties may be released slowly relative to new emerging threats. VPC seed systems are complex and face several challenges: poor-quality seed of existing varieties, low adoption rates of improved varieties, and slow varietal turnover, limiting yield increases and farmers' ability to adapt to new threats and opportunities. Addressing these challenges requires first identifying key knowledge gaps on seed systems to guide research for development in a holistic and coherent way. Working together across 10 crops and 26 countries in Africa, Asia, and Central and South America, the CGIAR seed systems research community has developed a "Toolbox for Working with Root, Tuber, and Banana Seed Systems," which introduces 11 tools and a glossary to address four major gaps: (1) capturing the demand characteristics of different types of farmers; (2) identifying effective seed delivery pathways; (3) ensuring seed health and stopping the spread of disease; and (4) designing effective policies and regulations. We describe the toolbox and its creation and validation across 76 crop-and-country use cases, and illustrate how the tools, applied individually or in combination, are addressing the key knowledge gaps in RT&B seed systems. The tool developers are actively working to scale the toolbox, including identifying new partners and models for collaboration, developing new tools, and supporting new applications in VPCs, as well as for fruit, vegetable, grain, and pulse seed systems.

11.1 Introduction

Quality seed, i.e., healthy, at the right physiological stage, in good physical condition, and of an appropriate variety (McGuire and Sperling 2011; Bentley et al. 2018), is the basis of all agricultural productivity. Roots, tubers, and bananas (RT&B) are backbones of food security in tropical and subtropical regions, which overlap considerably with the so-called least developed countries (LDCs). Bananas (including plantains), cassava, potato, sweetpotato, and yam are vegetatively propagated crops (VPCs) and, as such, their planting material or *seed* (suckers, stems, tubers, vines, roots) is bulky, perishable, prone to seed degeneration, and has low multiplication rates (Bentley et al. 2018). Farmers overwhelmingly use seed from previous harvests for the next season, exchange seed with family and friends, or buy seed from informal seed traders, with little or no access to certified seed and improved varieties (Sperling et al. 2020). This places the farmers at the center of VPC seed systems and at the heart of research to support the development of these systems. Research and policy on seed systems has traditionally focused on sexually propagated crops (SPCs), leaving major knowledge gaps for VPCs. In this chapter, we present the "Toolbox for Working with Root, Tuber, and Banana Seed Systems" (referred to as "the toolbox"), a collection of biophysical and socioeconomic tools which together offer a systematic approach to diagnose, evaluate, and improve the seed systems of banana, cassava, potato, sweetpotato, and yam. The chapter is structured around four knowledge gaps, discussed below, that prevent seed systems from functioning effectively and limit dissemination of improved varieties (McEwan et al. 2021a). These gaps were identified while conducting the many case studies that applied the toolbox across crops and contexts worldwide.

We start the chapter by describing the four main knowledge gaps and the challenges facing seed systems for RT&B crops. Then we describe how the toolbox was developed, its context among similar initiatives, the entry points for using the toolbox, combinations of tools, and the level of use. We then describe the tools and discuss how they have been used and the results achieved. We finish the chapter with lessons learned and perspectives.

11.1.1 Key Challenges and Knowledge Gaps

Seed systems for RT&B crops in the tropics and subtropics face three main challenges. First, poor-quality seed limits the yields of existing varieties. In the case of potato in sub-Saharan Africa (SSA), for example, Harahagazwe et al. (2018) estimated that the absolute yield gap was 58.3 t/ha, and they identified poor-quality seed as the top driver of the yield gap. The second and third challenges are related to improved varieties: low adoption and slow varietal turnover. In SSA, Walker et al. (2015) found that the adoption ceiling of modern varieties (improved varieties released after 1970) was less than 40% of the total area, with cassava having the highest adoption rate (39.7%) and banana the lowest (6.2%). Similarly, the average varietal turnover (expressed as varietal age) was 15.2 years (Thiele et al. 2020), with potatoes having the slowest (19.4 years) and bananas the fastest turnover (10.2 years) (Walker et al. 2015). The combination of poor-quality seed, low adoption rates, and slow varietal turnover affects farmers' livelihoods, because yield capacity is reduced and farmers are unable to seize genetic gains obtained by crop breeders (Rutkoski 2019; CGIAR Excellence in Breeding Platform 2011), as they do not benefit from improved varieties with traits such as better yields, high nutritional value, resistance or tolerance to biotic and abiotic stresses, and market-preferred characteristics.

Addressing these challenges is a complex task and requires first identifying key knowledge gaps on seed systems to guide research for development (R4D) in a holistic and coherent way. McEwan et al. (2021a) described four gaps: (1) capturing the demand characteristics of different types of farmers; (2) identifying effective seed delivery pathways; (3) ensuring seed health and stopping the spread of disease; and (4) designing effective policies and regulations.

11.1.2 Toolbox

Filling in these knowledge gaps requires "tools," i.e., methods, models, approaches, or information and communication technologies (ICT), that can be applied systematically and repeatedly in different contexts to study, diagnose, evaluate, and ultimately generate evidence to improve RT&B seed systems. The toolbox includes 11 biophysical and socioeconomic tools and a glossary, each designed to address specific knowledge gaps (Table 11.1). The general goal of the toolbox depends on the user: researchers with the goal of studying seed systems; policymakers with the goal of developing, strengthening, and supporting seed systems; practitioners with the goal of designing, implementing, and evaluating seed system projects; and plant breeders who define product/client profiles (Andrade-Piedra et al. 2020).

The toolbox was created by the *Seed Systems Community of Practice of the CGIAR Research Program on Roots, Tubers and Bananas (RTB)*, a group of biophysical and social scientists. Since 2012, this group has designed and tested the tools in East, West, and Southern Africa; Central, South, and Southeast Asia; and Latin America (Table 11.2). Most of the tools were adapted from other crops or from other fields of study and were usually developed for one crop and then adapted for the others. The tools integrate gender-responsive strategies as much as possible to enable users to explore different interests, preferences, opportunities, and constraints for different categories of users and social groups. The tools vary in the level of expertise and time required to implement them. For example, the multi-stakeholder framework (MSF) requires basic expertise on seed systems and workshop facilitation, and it is applied in a period of up to 2 months (Bentley et al. 2020), while new applications of the seedHealth model in R currently require collaborators with experience using the R programming environment and, if analyses are intended for publication in scientific journals, might take up to a year for completion (Garrett and Xing 2021). Documentation for each tool includes a peer-reviewed journal article discussing how the tool was created or adapted and applied, a user guide, a description sheet, communication materials, and software (if applicable), all available at https://tools4seedsystems.org/ (Andrade-Piedra et al. 2020).

11.1.3 Other Initiatives

The challenge of improving seed systems has inspired the development of various initiatives. For example, Seed System (https://seedsystem.org/) provides guidance to improve seed security in high stress and vulnerable areas using tools such as the seed system security assessment (SSSA) (Sperling 2008). The Seed Commercial, Legal, and Institutional Reform (SeedCLIR) diagnostic tool addresses the role of legal and institutional components (USAID 2013). Bioversity International's

Table 11.1 Tools in the RTB toolbox, their purpose, and the knowledge gap each addresses

Tool	Purpose	Seed system knowledge gaps[a]			
		Gap 1: seed demand	Gap 2: seed delivery	Gap 3: seed health	Gap 4: policies and regulations
1. Multi-stakeholder framework (MSF)	Identify stakeholders, coordination breakdowns, bottlenecks; rapid assessment of seed availability, access, and quality	✓	✓	✓	✓
2. Impact network analysis (INA)	Evaluate the likely outcomes for the current seed system, and for potential interventions in it, in scenario analyses		✓	✓	✓
3. Seed Tracker (ST)	Organize information to enable quality seed production, certification, and market linkages and to integrate the seed value chain		✓	✓	✓
4. Integrated seed health (ISH) approaches and models	Evaluate how a scenario for the potential use of formal seed, disease resistance, and on-farm management are likely to affect crop health			✓	✓
5. Seed tracing (STg)	Map parts of the seed system such as volume of seed distributed, transaction types, or types of varieties		✓		
6. Small N exploratory case stud y(SN)	Understand farmers' use of seed	✓	✓		
7. Four-square method (FSM)	Characterize seed and variety diversity and use	✓	✓		
8. Means-end chain analysis (MEC)	Understand farmers' motivations for preferring particular seed types and sources and the expected benefits	✓	✓		
9. Experimental auctions (EA)	Elicit individual's willingness to pay (WTP) and willingness to accept (WTA) seed traded in the market	✓			✓

(continued)

Table 11.1 (continued)

Tool	Purpose	Seed system knowledge gaps[a]			
		Gap 1: seed demand	Gap 2: seed delivery	Gap 3: seed health	Gap 4: policies and regulations
10. Seed regulatory framework analysis (SRFA)	Analyze seed regulatory frameworks and implications for vegetatively propagated crops from different stakeholder perspectives			✓	✓
11. Sustainable early generation seed business analysis tool (SEGSBAT)	Prepare a business plan and analyze the financial sustainability of a seed enterprise	✓	✓		
12. Glossary of root, tuber, and banana seed systems	Cites published literature to define and explain important terms in seed systems research and development	✓	✓	✓	✓

[a]Gap 1, capturing demand for varieties and seed; Gap 2, identifying effective seed delivery pathways; Gap 3, ensuring seed health; Gap 4, effective policies and regulation

Resource Box for Resilient Seed Systems (http://www.seedsresourcebox.org/) emphasizes participatory plant breeding approaches and linking seed producers to local and international gene banks, while their Seeds for Needs initiative (https://www.bioversityinternational.org/seeds-for-needs/) uses access to genetic resources to minimize risks from climate change. Other relevant initiatives include the Integrated Seed Sector Development approach (https://issdseed.org/) and SeedSAT (https://seedsat.org/), among others.

The toolbox introduced in this chapter builds on these initiatives and is designed to be complementary and to fill a neglected niche. For example, the MSF presented below was adapted from the SSSA for targeted application with RT&B crops. The toolbox also includes tools that more explicitly address crop health in seed systems and strategies for protecting seed health which are particularly important in VPCs. We also provide scenario analysis to inform decision-making among potential strategies for deploying new varieties, sampling for disease, and managing disease.

Although several other seed system-oriented educational products and research or development toolkits exist, the toolbox is unique in its breadth of coverage of topics and disciplines, its focus on the specific needs of major VPCs, and its depth of peer review and scientific validation in real-world contexts before the tools were released.

Table 11.2 Use of the tools across countries and crops

Country	1. Multi-stakeholder framework (MSF)	2. Impact network analysis (INA)	3. Seed Tracker (ST)	4. Integrated seed health (ISH)	5. Seed tracing (Stg)
Burundi	Banana (6)[a]				
Cambodia		Cassava (4, 10)			Cassava (4, 10)
Democratic Republic of the Congo	Cassava (6)				
Ecuador	Potato (6, 22)	Potato (7)		Potato (8)	
Ethiopia	Teff, wheat (20)				Potato (33)
Georgia	Potato (5)	Potato (5)		Potato (5)	
Ghana	Banana, cassava (6)				
Haiti		Banana, mango (9, 12)			
Kenya	Banana, potato (6, 19)	Potato (13)		Potato (8)	
Lao People's Democratic Republic		Cassava (4, 10)			Cassava (4, 10)
Malawi	Cassava, potato (6)				
Mozambique	Cassava (6)				
Nigeria	Cassava, yam (6, 29, 34)		Cassava, yam (28, 35)		
Nicaragua	Cassava (6)				
Peru	Potato (6)				
Philippines					Forages (18)
Rwanda	Sweetpotato (6)				Cassava (15)
Sierra Leone	Cassava (6)				
Thailand		Cassava (4, 10)			Cassava (4, 10)
Uganda	Banana, sweetpotato (2, 6)	Sweetpotato (3)			
United Republic of Tanzania	Cassava, sweetpotato (6, 24)		Cassava (35)	Sweetpotato (25)	
Vietnam	Cassava, potato (14)	Cassava (4, 10)			Cassava, forages (4, 10, 18)

(continued)

Table 11.2 (continued)

Country	6. Small N exploratory case study (SN)	7. Four-square method (FSM)	8. Means-end chain analysis (MEC)	9. Experimental auctions (EA)	10. Seed regulatory framework analysis (SRFA)	11. Sustainable early generation seed business analysis tool (SEGSBAT)
Burkina Faso						Sweetpotato (30)
Cameroon	Banana (23)					
Ethiopia	Potato (32)		Sweetpotato (26)			Sweetpotato (30)
Ghana						Sweetpotato (30)
Kenya			Sweetpotato (26)		Potato (19)	Sweetpotato (30)
Lao People's Democratic Republic				Cassava (11)		
Malawi						Sweetpotato (30)
Malaysia		Forest species (1)				
Mozambique						Sweetpotato (30)
Nigeria	Cassava (29)				Cassava (31)	Sweetpotato (30)
Rwanda						Sweetpotato (30)
Uganda	Banana (16)	Banana (16, 21)	Banana (17)			Sweetpotato (30)
United Republic of Tanzania			Potato (27)			Sweetpotato (30)
Vietnam					Cassava, potato (14)	
Zambia						Sweetpotato (30)

[a]References 1, Aini et al. 2017; 2, Ajambo et al. in preparation; 3, Andersen et al. 2019; 4, Andersen et al. 2020; 5, Andersen Onofre et al. 2021; 6, Bentley et al. 2018; 7, Buddenhagen et al. 2017; 8, Buddenhagen et al. 2022; 9, Dantes et al. 2020; 10, Delaquis et al. 2018; 11, Delaquis et al. unpublished data; 12, Fayette et al. 2020; 13, Gachamba et al. 2022; 14, Gatto et al. 2021; 15, Kilwinger et al. 2021b; 16, Kilwinger et al. 2019; 17, Kilwinger et al. 2020; 18, Leyte et al. 2021; 19, McEwan et al. 2021c; 20, Mulesa et al. 2021; 21, Mulugo et al. unpublished data; 22, Navarrete et al. 2019; 23, Nkengla-Asi et al. 2020; 24, Ogero et al. 2015; 25, Ogero et al. 2019; 26, Okello et al. 2018a; 27, Okello et al. 2018b; 28, Ouma et al. 2019; 29, Pircher et al. 2019; 30, Rajendran et al. 2017; 31, Spielman et al. 2021; 32, Tadesse et al. 2017a; 33, Tadesse et al. 2017b; 34, Wossen et al. 2020; 35, https://seedtracker.org/

11.1.4 Entry Points

Questions about seed systems (for research or for development projects) are the basis for selecting a tool. The following examples of questions are described in more detail elsewhere (Andrade-Piedra et al. 2020):

- For MSF: Who are the specific stakeholders of a seed system?
- For INA: What types of interventions are likely to lead to wider adoption of a new variety?
- For FSM: What local and improved varieties do farmers grow?
- For EA: What is the real market value for seed?
- For SRFA: What types of public policies and regulations are in place for the subject crops in a country?

These questions can be broadly grouped into the four knowledge gaps described above (seed demand, seed delivery, seed health, and policies and regulations), with each tool addressing at least one knowledge gap (Table 11.1). While some tools (e.g., the multi-stakeholder framework) address all knowledge gaps in an exploratory manner, others address one or two knowledge gaps at a deeper level, such as the four-square method and the means-end chain analysis that focus on understanding seed demand and seed delivery.

In addition to using questions about seed systems as the basis for selecting appropriate tools for a given case, tools can also be selected using two other entry points: the seed value chain (Fig. 11.1) and the project implementation life cycle (Fig. 11.2). A seed value chain includes components from plant genetic resources through breeding, early generation seed (EGS), decentralized multiplication, farmer and trader use, and markets and consumers (Fig. 11.1).

Tools from this toolbox may be selected and combined for implementation considering what tools might be important at each stage of a seed value chain (Fig. 11.1). First, a quick and comprehensive overview of the bottlenecks and gaps of the seed value chain can be conducted using the multi-stakeholder framework. Then, for planning optimal use of plant genetic resources, the seed regulatory framework analysis can provide input on relevant policies for genetic resource management, while the four-square method can provide input on what genetic resources would support variety development for the needs farmers express.

To inform crop breeding, the same tools can be used for evaluating plant genetic resources, along with means-end chain analysis and experimental auctions to provide information about the basis for farmer selection of variety traits and farmer willingness to pay for specific types of varieties, respectively. For planning EGS production, INA can evaluate how effectively seed movement is linked to the next stages of the system; ISH approaches and models can be used to evaluate how much seed would be needed for optimal farmer purchase of quality-declared seed to manage seed-borne disease; SEGSBAT can evaluate seed production needs for business efficacy downstream; and the Seed Tracker can be used to keep track of where seed is available and how it moves downstream, and it can be used in regulatory oversight.

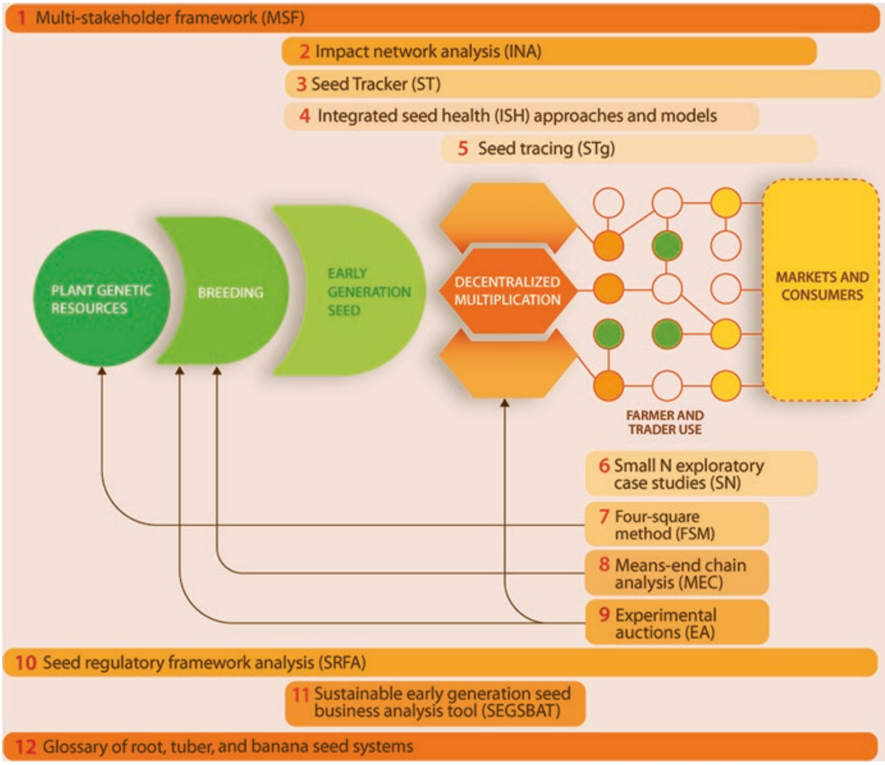

Fig. 11.1 The components of a seed value chain and the range of components for which each of the tools can be used. Tools corresponding to each number are listed in Table 11.1

For planning decentralized multiplication of seed, the same tools can be used as for EGS production, along with seed tracing to characterize seed movement based on surveys and group discussions. To evaluate options for improvements at the stage of farmer and trader use, small N exploratory case studies, the four-square method, means-end chain analyses, and experimental auctions all offer different perspectives on how farmers choose varieties, cultivation methods, and whether to purchase seed or save their own seed.

To understand the influence of markets and consumers on the seed value chain, the multi-stakeholder framework can be used to create an overview of all actors in the system. The seed regulatory framework sheds light on policy effects and policy options on seed markets. INA can evaluate how seed and crop products move through from EGS to the market. Seed Tracker and seed tracing can continue to track seed and product movement, and small N exploratory case studies can help to understand market decisions.

A project designed to improve seed systems typically has the stages illustrated in Fig. 11.2. The tools may be used at various stages in the project cycle to support regular evaluation and improvements. Most of the tools can be used in defining the

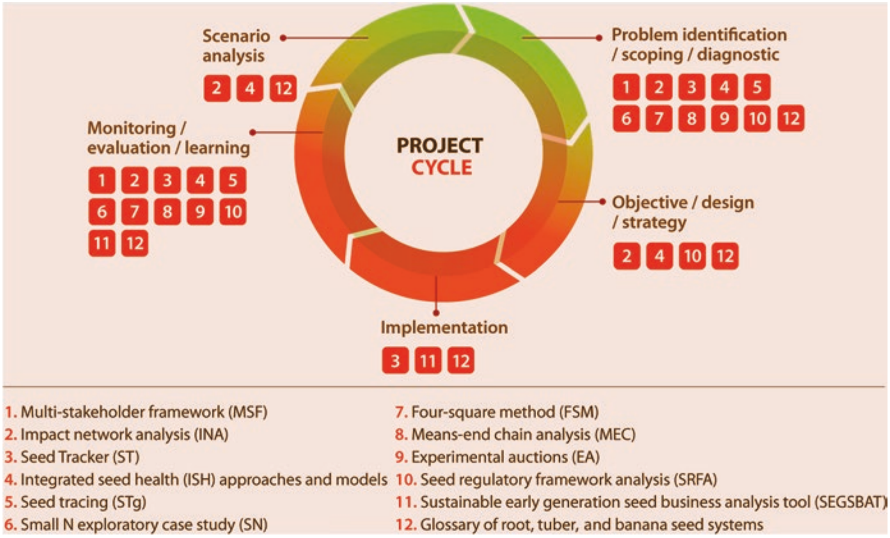

Fig. 11.2 A seed system project cycle and the tools that can be used at each stage. Tools corresponding to each number are listed in Table 11.1

problem the project will address and the strategy for addressing it. Some of the tools can be used during project implementation. All can be used as part of project monitoring and evaluation (M&E). Some tools are useful during scenario analysis to understand the results of M&E, to help the project succeed (Fig. 11.2).

11.1.5 Combining Tools

The tools gain strength when used together. For example, data from several tools can inform the scenario analyses provided by INA. And the results from INA can inform other tool applications (Fig. 11.3). In the Republic of Georgia, the MSF, INA, and ISH approaches were used together (Andersen Onofre et al. 2021).

11.1.6 Use of the Toolbox

The 11 tools in the toolbox have been applied on 10 crops in 26 countries for a total of 76 applications (Table 11.2, Fig. 11.4). Of the crops, cassava has the most applications (24), followed by sweetpotato (18), potato (17), banana (9), and yam (2). Besides RT&Bs, the tools have been applied on forage crops (twice), forest species (once), mango (once), and on teff and wheat (once each). The tools have been applied in 15 countries in Africa, 7 in Asia, and 4 in Central and South America

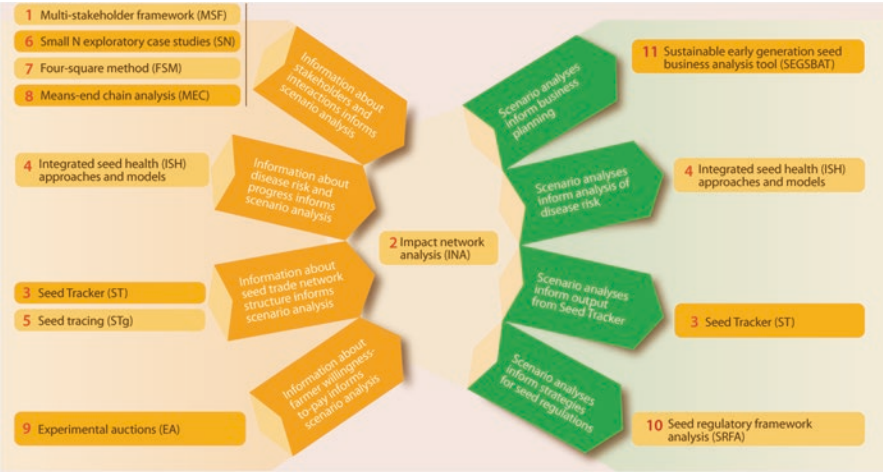

Fig. 11.3 Tools can be used together to inform seed system strategies. For example, INA can use data from other tools as input and can provide output data for use by other tools

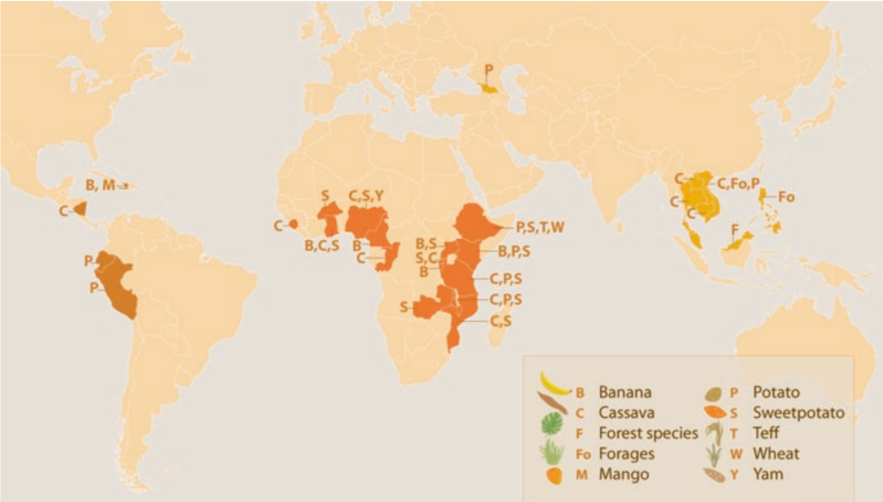

Fig. 11.4 Countries and crops in which projects have applied the tools in this toolbox

(Fig. 11.4). The tools have been used most frequently in Kenya and Uganda (six times each), Tanzania and Ethiopia (five each), and Nigeria and Vietnam (four each). The tools most often applied are MSF (25 applications), SEGSBAT (11), INA (10), and seed tracing (7).

11.2 Tools

11.2.1 Multi-stakeholder Framework (MSF)

Grasping the complexity of seed systems is a challenge for those who are working in a new location or crop, whether to understand the existing seed systems or to conduct projects to improve them. The multi-stakeholder framework (MSF) addresses this challenge by providing a snapshot of a seed system in a specific crop, location, and time.

The MSF is an adaptation of the seed system security assessment (SSSA) (Remington et al. 2002; Sperling 2008; FAO 2015) built around concepts derived from food security: access, availability, and utilization (quality). The MSF considers seed regulations and policies, sustainability, and gender as crosscutting themes. The MSF was tested in 13 case studies, finding that gender roles are important in seed systems and that ignoring the differences between women and men can lead to coordination breakdowns that can threaten seed security (Bentley et al. 2018). The MSF has been applied in 17 countries and 7 crops (Table 11.2).

The MSF has been used to:

- Understand the seed sourcing behavior of cassava farmers and to identify entry points for decentralized stem multipliers (DSMs) in Nigeria (Pircher et al. 2019).
- Identify stakeholders in the potato production system in Georgia (Andersen Onofre et al. 2021).
- Review a sweetpotato project promoting a systematic reflection from different stakeholder perspectives in Tanzania (Ogero et al. 2015).
- Identify participants and design key informant interviews and focus group discussions to explore regulations for potato and cassava seed in Vietnam, Nigeria, and Kenya (Wossen et al. 2020; Gatto et al. 2021; McEwan et al. 2021c; Spielman et al. 2021).
- Identify stakeholders and the main features and bottlenecks of potato seed systems to refine research questions and design a household survey in Ecuador (Navarrete et al. 2019).
- Estimate seed security of teff and wheat in Ethiopia (Mulesa et al. 2021).

The MSF can be used as the starting point for a comprehensive analysis of bottlenecks in a seed system, to monitor an intervention (McEwan et al. 2021a), and for cross crop/region comparison among interventions (Bentley et al. 2018). Users of the MSF usually gain an understanding of the complexity in structure and interactions between stakeholders, including tensions which are not obvious prior to using the tool. The MSF is multidisciplinary and transdisciplinary, which may be a challenge during workshops or field visits, but also a benefit, encouraging the users to take a more holistic view of seed systems.

11.2.2 Impact Network Analysis (INA)

Impact network analysis (INA) is a tool for anticipating the outcomes of a seed system project that is underway or in planning. It is a new tool based on modeling a system as a combination of (1) a network of people or institutions who may influence each other and have transactions and (2) a network of the movement between farms of seed, varieties, and potentially of pathogens or pests (Garrett et al. 2018; Garrett 2021a, 2021b). Results from scenario analyses support decision-making by researchers, policymakers, and practitioners.

INA includes an R package that simulates outcomes for scenarios defined by the user (Garrett 2021a, 2021b, updates at garrettlab.com/ina/). It provides scenario analyses in stochastic simulations to evaluate questions such as the following: (1) How likely is a new variety to spread through a seed system, and how could changes in the system make it spread further? (2) What will be the most effective sampling strategy for monitoring disease spread through a seed system? (3) What strategy for managing disease spread is likely to be most effective? (4) Do men and women (and other social groups) receive equitable benefits from the current seed system, or what changes would be necessary?

INA has been applied in combination with the MSF and the ISH approach to help design a new potato seed system in the Republic of Georgia, taking into account risks from diseases such as potato wart (caused by *Synchytrium endobioticum*), and identifying key locations to monitor the disease to prevent losses (Andersen Onofre et al. 2021). INA is currently being applied with seed tracing to develop strategies for deploying clean seed to slow the spread of cassava mosaic disease in SE Asia (Delaquis et al. 2018; Andersen et al. 2020). The INA framework was applied to understand potato seed systems in Ecuador (Buddenhagen et al. 2017) and sweetpotato seed systems in Uganda (Andersen et al. 2019), where these two studies provided groundwork for applications in new systems. INA is also currently being applied in collaboration with the Kenya Plant Health Inspectorate Service (KEPHIS) to evaluate strategies for managing disease in Kenyan potato seed systems (Gachamba et al. 2022) and for banana and mango disease and pest risk assessment in Haiti and the Caribbean (Dantes et al. 2020; Fayette et al. 2020).

11.2.3 Seed Tracker (ST)

The Seed Tracker (ST) is an ICT tool that digitally links seed value chain actors, tracks seed production, and organizes seed information for stakeholders. The ST's digital data collection tools are usable on any Internet-enabled device with an Android operating system. It offers secure individual and group accounts and a database with analytics and geographic information system (GIS) tools. The ST covers all stages of the seed value chain and the needs of stakeholders: researchers, extensionists, regulators, seed producers, traders, service providers, and farmers. It supports seed production planning, seed traceability, seed inventory management, and quality assurance. The Seed Tracker allows regulatory authorities to monitor the production of certified seed and allows real-time information exchange between seed producers and regulators. It is also a business tool that helps to link seed producers with customers. It offers real-time information on seed production by seed class, variety, volume, and location. The ST can be customized to fit different crops, national seed regulations, and user-defined needs. ST can potentially map gender-disaggregated information which policymakers and extension services can use to inform seed delivery strategies.

11.2.4 Integrated Seed Health (ISH) Approaches and Models

Seed systems that spread diseases or pests can do more harm than good. Understanding seed degeneration, and how to manage it, is important for supporting better seed systems. The "integrated seed health approach" combines three management components to help farmers decide how to manage seed health: periodic purchase of healthy seed, disease resistance, and on-farm disease management (Thomas-Sharma et al. 2016). A model called "seedHealth" identifies the combinations of these three components most likely to be successful, to support training and decision-making by researchers, policymakers, and practitioners (Thomas-Sharma et al. 2017; using an online dashboard link at garrettlab.com/seedhealth/; Garrett and Xing 2021).

At regional scales, a fourth component of ISH approaches is phytosanitary management to prevent the introduction of new pathogens and pests. The seedHealth model can be used to answer questions such as: (1) How frequently would it benefit farmers to buy certified/quality-declared seed, and/or to access a new variety? (2) What would the effect be of strengthening particular types of on-farm management, e.g., training to support positive selection? (3) Do differences in men's and women's access to, and use of, the components of seed health management lead to different levels of success?

ISH approaches and the seedHealth model are being used to study seed health in systems such as sweetpotato in Tanzania (Ogero et al. 2019) and potato in Kenya (Gachamba et al. 2022). The ISH approach has been applied in combination with the MSF and INA to help design a new potato seed system in the Republic of Georgia that protects against the spread of diseases such as potato wart, balancing on-farm management, resistant varieties, and new seed certification standards (Andersen Onofre et al. 2021). Seed health in a potato system in Ecuador was studied to support "management performance mapping," identifying locations in the Andes and Kenya where support for positive selection of farmer-saved seed is likely to have the greatest benefit (Buddenhagen et al. 2022). The seedHealth model can also be applied to evaluate better phytosanitary standards, to address the trade-off between higher availability of seed and poorer seed health (Choudhury et al. 2017). In banana bunchy top management, the model has been used to visualize and predict the strategies for managing disease spread and seed degeneration and to compare the performance of specific control options under different field conditions (I. Nduwimana, pers. comm.).

11.2.5 Seed Tracing (STg)

An important issue in the seed systems of RT&B is how new varieties diffuse. These systems are mostly informal, so the exchange between farmers is the main avenue for distributing new varieties. Seed tracing can be used to understand the diffusion of seed from formal to informal networks, and within farmer networks, thus providing strategic information for seed interventions and for policymakers.

In Ethiopia, a seed tracing study found that an NGO distributed seed potato of new varieties to wealthier farmers, who shared seed tubers frequently, including with poor farmers who rarely shared seed (Tadesse et al. 2017b). The wealthier farmers were key in variety diffusion, but also potentially in spreading pests and diseases.

Among Rwandan cassava farmers, seed tracing was used to inform the design of commercial seed businesses (Fig. 11.5). As in the Ethiopian case, better-off growers were more likely to obtain a new variety from formal sources, while poor farmers accessed new varieties from fellow farmers. Most (60%) seed transactions were for

Fig. 11.5 Moving cassava stakes and banana suckers between two farms. Seed tracing can map such exchange networks. (Photo: F. Kilwinger/WUR)

cash, suggesting that there are market opportunities. Yet, they were all one-time acquisitions. Once they obtained the variety, all farmers multiplied their own material, and 80% shared this with fellow farmers (Kilwinger et al. 2021b). This is common with the introduction of new VPC varieties: after a first spike of demand, the new variety gets absorbed into the informal seed system (Barker et al. 2021), discouraging commercial seed businesses.

A study of legume seed (Almekinders et al. 2020) found that men most often shared with men, and women with women, but men shared with women more often than the other way around. Such patterns of gendered seed flow could have implications for introducing new varieties. Yet, there was little effect on who the seed eventually spread to. The study allowed the project to report to donors that it had reached an estimated 2.5 million farmers in Africa through direct distribution and spontaneous diffusion of seed over the course of the project (Almekinders et al. 2020; Sikkema 2020).

11.2.6 Small N Exploratory Case Study (SN)

A small N exploratory case study collects data on formal and informal seed systems of a crop at the level of the farmers: what varieties do they grow and what are their patterns of seed saving, replacement, and sourcing? This is useful when diagnosing a seed system and identifying the challenges in improving local availability and access to quality seed: a first step that leads to deeper reconnaissance and seed system intervention. Typically, the core of the data collection is a survey with well-targeted questions for 35–50 farmers in a few communities. Because seed use practices, variety preferences, and needs of better-off and poor farmers often differ, it is worthwhile to collect data on both types of farmers and on male and female farmers.

A small team can collect the data relatively quickly. These inexpensive studies can be designed and carried out by staff members of an NGO or an agency that is active in the area and may later support seed activities. In contrast to surveys with many farmers and hired enumerators (i.e., large N surveys of 400 farmers or more), small N surveys can be enlightening for the data collectors, who may later help to implement the seed project. Our survey experience in Nigeria showed that joint analysis and discussion of the data were important learning opportunities for the local staff to arrive at a joint understanding of the cassava seed systems of the farmers they worked with (see Pircher et al. 2019).

This type of study belongs to a family of small N approaches (White and Phillips 2012) and has proven to be publishable, especially when gathering the first information about a seed system. For example, in the RTB case of banana seed systems, there was limited understanding of how management of the mat and suckers influenced variety choice and how it related to the farmer's age and gender (Kilwinger et al. 2019). In these situations, the additional information was acquired through semiformal interviewing or focus group discussions and use of the four-square method (see below).

11.2.7 Four-Square Method (FSM)

The four-square method (FSM) originally meant identifying a community's common, unique, and endangered crop varieties for genetic conservation (Grum et al. 2008). It comprises four squares that are drawn on the ground or on a chart. Each of the four squares holds the names of varieties of interest based on their abundance, i.e., if a variety is grown by many or few households, on a large or a small area:

1. Many households on large area.
2. Many households on small area.
3. Few households on large area.
4. Few households on small area.

The FSM has been adapted to assess crop diversity and popularity within a community and to create discussions around seed systems. The method can generate an inventory of varieties grown in a particular place and discuss their importance with farmers. Such information helps to identify seed interventions needed to conserve crop varieties and to highlight desirable traits in new varieties. The classification can also be a quick way of assessing the penetration of new varieties or changes in the popularity over time in response to seed systems or environmental stressors (Simbare et al. 2020). The FSM is often used in a focus group discussion with men or women to capture gender-related differences in appreciation of varieties and their traits (Mulugo et al. 2021).

The FSM has been used to study:

- The changes in varietal diversity of East African highland bananas in banana bunchy top disease outbreak areas of Burundi (Simbare et al. 2020).
- Farmers' production objectives regarding banana diversity in central Uganda (Kilwinger et al. 2019).
- Cassava diversity, loss of landraces, and farmers' preference criteria in southern Benin (Agre et al. 2016).
- Yam diversity and production in Southern Ghana (Nyadanu and Opoku-Agyeman 2015).
- Varietal diversity and genetic erosion of cultivated yams in Togo (Dansi et al. 2013).
- Seed interventions and cultivar diversity in pigeon pea in Eastern Kenya (Audi et al. 2008).
- Farmers' limited uptake of tissue culture banana seed in central Uganda (Mulugo et al. unpublished data).

In all these cases, the FSM was complemented with other methods such as literature review, key informant interviews, Venn diagrams, participatory value chain mapping, participatory rapid market appraisal, household surveys, and other tools of the toolbox, e.g., small N exploratory case study.

The FSM has been used to assess different seed system contexts including (1) before an intervention to understand the existing seed systems and to identify key issues for the project and (2) during interventions to monitor or evaluate them. The FSM creates a versatile overview and has been adapted elsewhere in dietary diversity studies (Aboagye et al. 2015) and gender studies in banana seed systems (Nkengla-Asi et al. 2020). The results can help to identify entry points for further research, for example, identifying varieties to study in greater depth using INA (I. Nduwimana, pers. comm.). Nkengla-Asi et al. (2020) adapted the method to classify household seed decision-making based on the level of responsibility and consultation between men and women, to reveal areas of common understanding and potential conflict. Other uses of the method could be developed.

11.2.8 Means-End Chains (MEC)

Means-end chain (MEC) analysis is an approach from the field of consumer studies developed in the 1980s (Reynolds and Gutman 1988). Since its development, the method has been applied in diverse fields such as tourism, food quality and preference, and sustainable behavior. Recently, it has also been used to understand how farmers evaluate, and why they value, different agricultural products, practices, and innovations (e.g., Okello et al. 2019; Urrea-Hernandez et al. 2016). The method is based on several psychological theories and takes into consideration differences among individuals' experiences. The means-end chain analysis identifies such differences as respondents are invited to select and verbalize their own personally relevant attributes to evaluate a product, service, or practice and relate those to their personal values (Walker and Olson 1991).

The method is promising in cross-cultural and exploratory research as it avoids forcing respondents into predetermined categories (Watkins 2010). And the psychological theories on which the method is based are similar to those underlying new approaches to understand adoption (Kilwinger and van Dam 2021a). For example, the framework to understand technological change developed by Glover et al. (2019) is based on the theory of affordances (Gibson 1977), which has considerable overlap with the personal construct theory (Kelly 1955). Also, Tricot trials (van Etten et al. 2019) make use of the principle of asking farmers to differentiate between three choices.

One MEC study with Andean potato farmers found that farmers and experts understand seed quality differently (Urrea-Hernandez et al. 2016), suggesting that understanding farmers' perceptions of quality seed is important for developing effective seed interventions. A MEC study of farmers' perceptions of formal and informal sources of banana planting material in Uganda showed that all farmers (large and small, male and female) had similar goals, but considered different variety traits and the benefits derived from them to achieve those goals (Kilwinger et al.

2020). Some of these Ugandan farmers expected to find the planting material of these varieties in nurseries, while others planned to get it from fellow farmers. These farmers care about variety traits, but also about the source of their planting material. It is important to understand which variety traits farmers prefer, as well as how they like seed to be delivered.

11.2.9 Experimental Auctions (EA)

A key challenge in developing VPC seed systems is understanding and predicting demand for different types and quality of planting material. The viability of the seed system depends on whether farmers perceive the seed as a quality planting material and whether they are willing to pay a premium for that quality. To get those insights, various types of experimental auctions can elicit "true willingness to pay." This tool allows comparing the premium value given to seeds, varieties, or variety traits by different groups, e.g., men and women farmers. This tool can also map out seed market size and segments for various types of customers. Outcomes can support more competitive pricing policies, attract different types of seed producers and customers, and nicely complement other tools (e.g., SEGSBAT described below).

Experimental auctions have recently been conducted among bean farmers in Tanzania and cowpea farmers in Ghana, to evaluate their willingness to pay for certified, quality-declared, and recycled seed, concluding that farmers were willing to pay a slightly higher price for what they perceived as better seed (Maredia et al. 2019).

There has been less use of experimental auction approaches with vegetatively propagated crops. Due to the economic differences between VPC planting material and grain seeds, the method needs to be further evaluated and adapted (several studies to do this are underway led by members of the toolbox group). However, the method has yielded useful preliminary results which are already shaping seed system strategies. In Rwanda, this tool was applied in 29 villages in six leading sweetpotato production areas to estimate willingness to pay for high-quality sweetpotato planting materials and drivers of the demand for these vines (Fig. 11.6). The study also estimated willingness to pay a premium for biofortified varieties (rich in provitamin A) as opposed to the non-biofortified local ones. The preliminary results showed that true willingness to pay a price premium for quality attributes is significantly higher than the current price for the sweetpotato seed.

In Lao PDR, 21 experimental auctions in cassava areas around the country unearthed large differences in stem prices linked to villages' historical experiences with commercial cassava production (Delaquis et al. unpublished data; Fig. 11.7). In all sites, bids were higher for phytosanitary-tested seed and elite varieties than for farmer seed. The auctions also elicited how many bundles of seed were desired, which varied widely, demonstrating different seed purchase strategies (purchasing a few bundles for testing vs. going all-in and buying enough to replace the farmer's whole supply). Demand curves generated from the results are also informing early

Fig. 11.6 A Rwandan farmer, highest bidder for the sweetpotato vines in a second price experimental auction. (Photo: S. Rajendran/CIP)

stage, clean seed multiplication initiatives in the country with price points and preferences that can shape areas of intervention and outgrower strategies. This example demonstrates the tool's use at several stages in the project cycle.

11.2.10 Seed Regulatory Framework Analysis (SRFA)

More than 95% of the seed of RT&B crops flows through informal channels (e.g., farmer saved, purchased from neighbors and local markets). Yet current seed regulatory frameworks do not recognize this and may act as a constraint to improving the quality of vegetatively propagated seed. Most national seed policies and regulations were developed using the experiences from grain seed, especially hybrids. The characteristics of RT&B crops, such as clonal reproduction and specific plant health constraints that contribute to seed degeneration, have not been fully recognized. This means that regulatory processes need to be revised to remain relevant

Multidisciplinary teams of researchers, together with seed regulators, have used the Seed Regulatory Framework Analysis Tool (McEwan et al. 2021b; Spielman et al. 2021) to assess the implications of current seed regulatory frameworks in Kenya, Nigeria, and Vietnam. The teams have asked if implementing regulations

Fig. 11.7 Lao farmers participate in an experimental auction for cassava planting stems in Lao PDR. (Photo: E. Delaquis/Alliance of Bioversity International and CIAT, WUR)

increases the availability and access to quality seed potato, for whom, and with what consequences. In Kenya, stakeholders are gathering around two key narratives. The first narrative, "quality at any cost," ties potato (and other VPCs) to national food security objectives, arguing that yields will only increase within a regulatory framework that provides certified seed at scale, minimizes the risk of pests and diseases, and protects the reputation of seed producers and the hard-earned credibility of the country's regulator. The second narrative, "local quality assurance," introduces "clean" (healthy) seed production models that build off the entrepreneurial spirit of smallholder farmers and their organizations and allows for more relaxed quality standards and informal trade (McEwan et al. 2021c).

In Kenya, the increased understanding that VPC seed faces different challenges than grain seed has led to separate regulations for vegetatively propagated crops, perhaps the first instance in sub-Saharan Africa. In Vietnam, despite strict regulations on the production and trade of VPC seed, the rules are weakly enforced. Instead, seed producers and traders signal quality to farmers through trust, reputation, and long-term relationships. This may be effective at a localized scale, but these informal systems are unlikely to accommodate expansion of the cassava and potato sectors and unlikely to effectively manage increases in pest and disease pressures that result from cross border trade or climate change (Gatto et al. 2021). In Nigeria, findings have led to decentralized policy and regulatory approaches to managing the cassava seed system, prioritizing investment in innovative capacity at the community and enterprise levels (Wossen et al. 2020).

11.2.11 Sustainable Early Generation Seed Business Analysis Tool (SEGSBAT)

The transition from breeder seed to pre-basic (i.e., first generation) seed production is a major bottleneck in the smooth functioning of a formal seed system. An early generation seed (EGS) company requires predictable revenues based on competitive and affordable prices for market-preferred varieties. Using the sustainable early generation seed business analysis tool (SEGSBAT) (Rajendran and McEwan 2021a, 2021b), public and private sector institutions in 11 countries in sub-Saharan Africa analyzed the financial sustainability of their sweetpotato EGS businesses (International Potato Center 2017). Multidisciplinary teams first determined accurate costs of EGS production which were then used to calculate the appropriate price of EGS products and formulate a pricing strategy to attract more customers, increase revenue, and create a positive net cash flow (Fig. 11.8). Partners in six countries improved continuity of funding and met at least 90% of their recurrent seed production costs from season to season. Most institutions reduced the gap between production and sales, which increased marketed surplus. By having a detailed cost structure, users identified and addressed production inefficiencies to reduce the cost of goods sold, e.g., by reducing the number of tissue culture

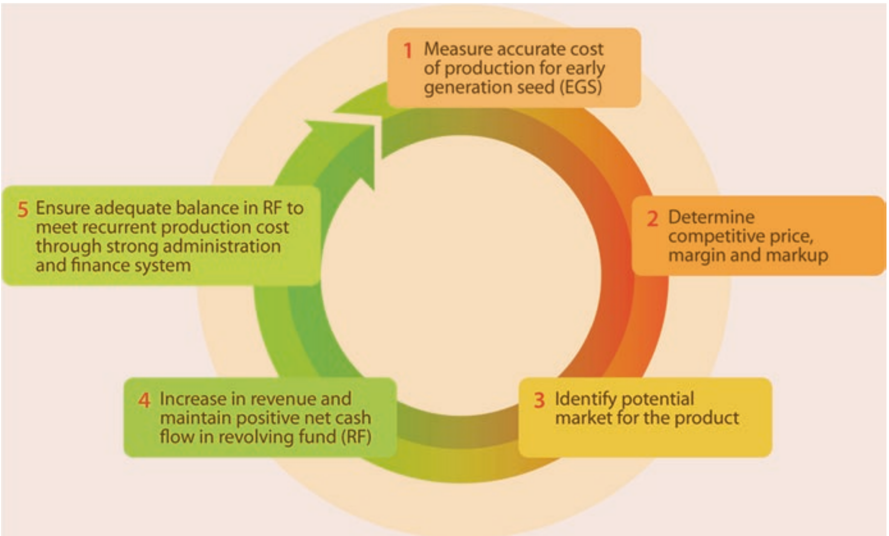

Fig. 11.8 Interconnection of financial performance and sustainability of sweetpotato EGS business. (Source: Rajendran and McEwan (2018))

plantlets required, and optimizing screenhouse production (Rajendran et al. 2017). Partners used SEGSBAT to develop business plans to guide sustainable sweetpotato EGS production, a first for RT&B crops in Africa (Gurmu et al. 2019).

Applying this tool revealed the specific challenges of determining the production costs of VPC seed, including (1) varying multiplication rates due to varietal characteristics, changes in temperature, growing conditions, and ratooning practices; (2) multiple stages in seed production, which may take place in different locations, i.e., pathogen tested tissue culture micro-propagation, hardening tissue culture plantlets for screenhouse multiplication before producing commercial seed in open fields; and (3) because seed is alive, wastage can be high and this must be factored into production costs.

Use of this tool highlighted that current methods for estimating seed requirements for production planning are inadequate (International Potato Center 2017). There are clear opportunities to continue working with public and private EGS producers and their networks of seed entrepreneurs to match SEGSBAT and other tools from the toolbox to the different stages in the product life cycle as part of the handover for commercialization from breeding outputs to seed value chain actors.

11.2.12 Glossary

Discipline-specific jargon can be a big obstacle to reaching a wider audience (Bullock et al. 2019). Seed system initiatives often provide a glossary of terms to help readers to understand key concepts. However, definitions may be generated by the authors themselves, to apply only within the context of their particular initiative. This can lead to confusion as many different interpretations arise and are misused or repeated out of context.

Common definitions are especially important for an emerging research area like seed systems, which brings together concepts from many different disciplines. The toolbox itself contains technical content from economics, behavioral science, network analysis, botany, agronomy, plant pathology, policy analysis, and gender studies, so most readers will encounter unfamiliar terms.

The glossary of RT&B seed systems developed for the toolbox (Delaquis et al. 2020) lends clarity to this issue by compiling definitions cited in literature across disciplines and providing the context of each term, references and links to the original sources, and the date of last modification. Over time, new terms can be added to the interactive glossary on the toolbox website, and existing definitions can be updated. Having definitions in one public place facilitates disambiguation and opens dialogue.

The glossary provides a stand-alone reference, supports the use of all tools in the toolbox by a wide audience, and can track changing definitions as seed systems research evolves and new concepts emerge, serving as a resource for anyone working on seed systems.

11.3 Conclusions

The development and use of the toolbox over a wide range of cases and contexts has led to several higher-level findings and lessons. Implementation has validated the great interest of public and private sector actors in diagnosing and improving VPC seed systems and those of other crops. The four knowledge gaps which formed the basis of this chapter emerged from reflection about these diverse experiences, a direct outcome of structured interactions between the toolbox development community of practice. Assembling the tools in a toolbox made them more accessible, provided an intuitive structure for new users, and helped to clarify which tools and combinations of tools are most useful for addressing different types of challenges. The modular structure with validated tools also inspired confidence and increased the value of lessons learned across crops and locations.

11.3.1 Outcomes

Applying the tools individually or in combination is generating outcomes by addressing key knowledge gaps in seed systems (Sect. 11.1.1; McEwan et al. 2021a) and facing the main challenges of RT&Bs: poor-quality seed of existing varieties, low adoption rates of improved varieties, and slow varietal turnover. Seed Tracker (ST) is helping seed growers and regulators to track yam and cassava seed production and marketing in Nigeria, Tanzania, and Brazil (Ouma et al. 2019; Kumar 2021; www.seedtracker.org/cassava). Tracking the seed improves the delivery of quality seed of improved varieties (knowledge gap 2) and the implementation of policies and regulations (knowledge gap 4). Four-square method (FSM) has been used to facilitate farmer understanding of optimal banana variety use and has helped stakeholders to appreciate the need for banana variety conservation in Uganda (Kilwinger et al. 2019; Mulugo et al. unpublished data), improving the capture of seed demand characteristics (knowledge gap 1).

Although the tools were designed to function as stand-alones, in several cases, they were used in combination to better address knowledge gaps. For example, in the Republic of Georgia, combining the multi-stakeholder framework (MSF), impact network analysis (INA), and integrated seed health (ISH) models provided direction for establishing a new potato seed system (Andersen Onofre et al. 2021). In Southeast Asia, combining INA, ISH, and seed tracing (STg) generated new understanding of cassava seed trade networks and the implications of their structure, guiding deployment of clean seed to manage an emerging cassava mosaic disease epidemic (Delaquis et al. 2018; Andersen et al. 2020). In Tanzania, combining MSF and ISH provided a rapid view of challenges to the sweetpotato seed system and the potential for new disease management strategies to provide economic benefits to growers (Ogero et al. 2015, 2019). These three examples show how the tools contribute to improve seed health and stop the spread of diseases (knowledge gap 3).

There are also many opportunities to link these tools with other methods or initiatives. Other RTB programs address disease testing and disease diagnosis in the field, because effective seed systems often depend on accurate diagnostic testing to protect seed health. For example, ST is being linked to *PlantVillage Nuru* (Mrisho et al. 2020), a smartphone-based artificial intelligence system for infield diagnosis of cassava mosaic disease (CMD) and cassava brown streak disease (CBSD). *PlantVillage Nuru* helps farmers to diagnose the problem and ST tells them where to get healthy seed. Potato seed systems in East Africa must address the spread of the pathogen *Ralstonia solanacearum*, causing bacterial wilt (Gachamba et al. 2022). The analysis of cropland connectivity, i.e., the importance of locations for the potential spread of crop-specific pathogens, has been used to evaluate crop risks for RT&Bs (Xing et al. 2020) and can provide networks for input in INA. In Rwanda, STg was combined with the rural household multiple indicator survey (RHoMIS) (van Wijk et al. 2020) and typology analysis (Hammond et al. 2020) to understand the cassava seed sourcing practices of different farm typologies (Kilwinger et al. 2021b).

While most of the tools strive to incorporate gender, there is a need for greater gender integration in existing tools and for stand-alone gender tools. For example, a study to validate the gendered MSF in Uganda revealed more nuanced gender dimensions in banana seed systems which will require the attention of extension services to address women farmers' limited access to banana varieties and to improve their knowledge of variety performance and the control of pests and diseases (Ajambo et al. in preparation). The tools could also be improved by putting them in the hands of multidisciplinary research teams at study design and implementation to allow for greater integration of social and gendered perspectives. Since the toolbox is a living resource, including stand-alone gender tools in the future will enhance its applicability for a wider range of research propositions by targeted R&D users.

Toolbox development has focused on building its research foundations through the portfolio of applications discussed above. The current portfolio gives examples of applying each tool and some combinations of them. With each use, lessons are learned, and the tools are adapted. The tools are designed to be flexible for new questions and systems. While the tools have initially been applied to RT&B crops, with their particular challenges for seed system development, the tools are also ready for wider application to grains, pulses, fruits and vegetables, and new VPCs. New tools are also in the pipeline, including one to co-develop seed delivery profiles with breeders and seed system scientists to design effective seed delivery (McEwan et al. 2021a).

11.3.2 Scaling

Following the validation of the tools in different crop and country combinations, we have turned our attention to understand how we can use scaling readiness concepts (Sartas et al. 2020) to promote wider use of the toolbox to realize our vision of different types of farmers accessing quality seed and improved varieties. Many seed innovations struggle to survive beyond project support. This may reflect a linear approach to technology adoption and the failure to consider the wider enabling factors around scaling.

Quality seed and improved varieties are technical innovations. But they are used within specific social and natural contexts. The tools provide diagnostic, methodological, and decision support. By promoting the findings and outcomes from using the tools, we seek to encourage a change in mindsets and new ways of thinking about how formal and informal seed systems function, the challenges and how to address them, and the required changes in infrastructure and investments. These elements come together as the toolbox innovation package. We have identified bottlenecks to scaling the toolbox, including lack of awareness by potential users and the need to provide training and mentoring opportunities for national seed system actors (e.g., national research institutions, extension, and NGOs).

To characterize the institutions and better target stakeholders who might use the toolbox, we conducted a landscape analysis of seed systems for sub-Saharan Africa (Cox et al. 2021). A communication strategy targeting different audiences, with video, infographic, and social media toolkits, has been implemented to support the launch of the toolbox. This process is helping us to identify new partners, networks, and types of collaborations to support scaling.

Our vision for the future is a global initiative that will foster collaboration around the tools to improve seed systems research on three levels: First, by continuing to refine the tools themselves. As tool use increases, feedback from more practitioners will promote improvement and synergies with other approaches. Second, through linkages to other initiatives and research programs, the toolbox can be a converging point for a greater community of practice, sharing wider experiences and novel approaches which may help to adapt the tools and expand the toolbox. Third, and most importantly, through continued documentation of impacts and improvements in seed system outcomes, findings can be integrated into higher-order evaluations and cross-case lessons for implementers and policymakers, deepening the scientific understanding and policy relevance of toolbox outputs. We envision the toolbox as a game changer to improve seed systems in the coming years.

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