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Policy and regulation in seed sector development for vegetatively propagated crops: Insights from Kenya, Nigeria, and Vietnam☆

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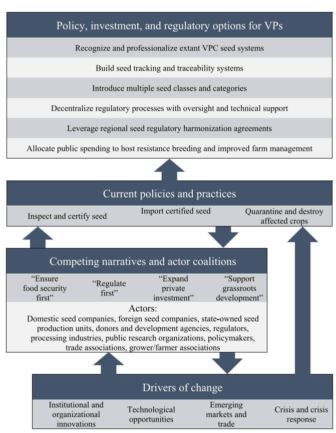
HIGHLIGHTS

- Seed quality assurance systems for vegetatively propagated crops are challenging.
- Biological and economic characteristics of VPCs are often binding constraints.
- We examine cassava and potato systems in Kenya, Nigeria, and Vietnam.
- Strict regulatory regimes limit availability of/access to quality seed.
- Policies to address this recognize multiple seed classes, production systems, and actors

GRAPHICAL ABSTRACT



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ABSTRACT

Context: In many low- and middle-income countries, smallholder farmers cultivating vegetatively propagated crops (VPCs) have limited access to quality planting material. This constraint can limit both the yield and returns to VPC cultivation. Yet policy and regulations designed to strengthen access to quality VPC planting materials and scale innovative programs that deliver these materials have been relatively unsuccessful to date. Part of the problem lies the unique biological and economic characteristics of vegetative propagation and its distinctness

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Vegetatively propagated crops
Seed market regulations
Seed quality assurance

from cereal crops that dominate narratives on seed sector reforms and the resulting policy and regulatory regimes.

Objective: The study analyzes both theory and evidence on existing and alternative models of regulation that may incentivize cost-effective multiplication and distribution in VPC seed systems and markets.

Methods: The study draws on case studies of policy and practice related to quality assurance regulations in four crop-country combinations: cassava in Nigeria and Vietnam, and potato in Kenya and Vietnam. The case studies rely on qualitative analysis that was conducted using a combination of key informant interviews, focus group discussions, analysis of regulatory documents, and analysis of publicly available secondary data.

Results and conclusions: The study describes five strategies for regulating VPC seed systems in our four crop-country combinations, each with its own generalizable costs and benefits. The application (or marginalization) of these strategies is often shaped by fluid coalitions of actors with competing interests and framing narratives, and driven by organizational innovations, technological opportunities, trade relationships, and crises that are crop- and country-specific.

Significance: These findings suggest that regulations designed around strict, centralized quality control systems tend to limit market size, while more localized production systems are limited by both capacity and reach. They also suggest the need for alternatives that balance a permissive regulatory regime with decentralized production systems, grassroots capacity development, market surveillance, and systems that integrate multiple approaches to quality assurance. A detailed set of policy recommendations follows from these findings that inform ongoing country efforts to revise VPC seed sector policies and regulations—reforms that are being pursued not only in the crop-country case studies highlighted here, but also in other countries in both Africa and Asia.

1. Introduction

Vegetatively propagated crops (VPCs) play an important and varied role in many agricultural systems and diets across many low- and middle-income countries (LMICs). An estimated 300 million people living in poverty in LMICs depend on at least one type of root, tuber, or banana crop for their livelihoods, and this figure is expected to grow over time (Thiele et al., 2017). Yet, while there are significant cross-country variations in yields for individual VPCs, per-hectare output and returns are well below what scientists believe is biologically and economically feasible under optimal agroclimatic conditions and crop management practices, particularly in smallholder production systems.

Use of quality planting materials can increase VPC yields (Almekinders et al., 2019). These planting materials—referred to as "seed" throughout this paper—include cuttings, stems, buddings, tubers, and other vegetative material used to asexually propagate a plant that is genetically identical to its parent. Both market and non-market systems that supply seed to farmers are integral to boosting VPC yields and, more generally, to supporting agricultural development (Cromwell et al., 1992; Jaffee and Srivastava, 1994; McGuire and Sperling, 2016).[1] Systems that deliver seed of acceptable quality are an essential complement to other yield-enhancing inputs and practices.

Most LMICs have explicit policies and regulations that govern seed systems. During the past two decades, some LMICs have introduced seed policy and regulatory reforms to seize new technological opportunities, accelerate agricultural growth and development, or leverage opportunities created by international trade agreements (Spielman, 2020; Spielman and Kennedy, 2016; Louwaars et al., 2013). But the unique properties of VPC seed are rarely recognized in these policy and regulatory reforms. Thus, this paper asks whether there are quality assurance systems that can increase availability and access to quality VPC seed for small-scale, resource-poor farmers and minimize the risk of seed- and soil-borne pests and diseases that threaten yields and incomes. In doing so, the paper distinguishes between a narrow view of the challenge—quality control, which is a reactive approach to ensuring seed quality—and a broader focus on quality assurance, a proactive approach that ensures seed quality throughout the entire production, processing, and distribution process involving multiple actors and interests. Seed quality assurance systems aim not only to meet regulatory standards for genetic, physiological, health, and physical characteristics but also to fulfil the expectations and requirements of end-users.

Reform efforts have not focused on VPC seed systems, in part because their unique phytosanitary, physiological, and physical properties set them apart from the cereal seed systems that are central to most national strategies for agricultural development. Common VPC seed challenges include low multiplication rates, bulkiness and perishability, and high susceptibility to pests and disease (Gibson et al., 2009; Fuglie et al., 2006). These characteristics limit the temporal and spatial reach of VPC seed systems and markets, and thus affect accessibility and affordability for smallholders.

VPC seed systems also face some of the same challenges as cereal seed systems. First, VPC seed are, in economic terms, experience goods, meaning that their genetic and physical quality cannot be observed by a farmer at the time of purchase, which makes VPC seed exchanges fundamentally problematic. The asymmetry of information between buyer and seller can crowd out sellers of higher-quality seed from the market and encourage the entry of sellers of lower-quality seed, thus reducing the efficiency gains expected from market exchanges (Akerlof, 1970).

In our context, the term "market" refers to any exchange of seed between two actors, and may include cash- or credit-based transactions between agents in a formal marketplace, or less formal barter or contract arrangements between neighbors or traders. When seed quality is not directly observable, the effectiveness of the quality assurance system can play a crucial role in shaping these markets—in shaping seed demand, supply, and the size, structure, and performance of the market. For example, regulations can reduce market size and seed supply if excessively stringent standards act as an entry barrier for new seed producers, thereby limiting competition and concentrating the market around fewer producers supplying seed at higher prices than might otherwise be expected in a competitive market. But these same regulations can also be used to prevent low-quality seed producers from entering and dominating the market, thereby crowding out high-quality seed producers and reducing the effective size of the market for quality seed. Striking the right balance between regulation and market flexibility is essential for expanding the seed market while ensuring seed quality. See Wossen et al. (2024, 2019) for examples of the consequences of this problem in VPC seed markets.

The literature on seed market frictions in LMICs suggests that quality assurance regulations can remedy the information problem (e.g., Tripp and Rohrbach, 2001; Morris, 1998; Tripp and Louwaars, 1997). Regulations such as seed certification and truthful labeling can inform farmers about the source of the seed, production date, expected germination rate, genetic and physical purity, and other indicators that signal quality to farmers, drive out low-quality producers, and increase the efficiency gains of market exchanges. Quality assurance systems internal to a seed producer can provide similar outcomes (Gildemacher et al., 2017), when accompanied by credible external monitoring that incentivizes compliance.

VPC seed systems—like all seed systems—are also influenced by political economy factors. Different actors construct competing framings, use different language, and create advocacy coalitions to advance their respective interests in policy change processes that influence seed systems (Hassena et al., 2016; Scoones and Thompson, 2011; Kloppenburg, 2010, 1988). In other words, we cannot analyze seed system policy from a purely technical perspective or with an economic efficiency analysis; we must also recognize that outcomes are shaped by relationships between the state, markets, and citizens.

To understand how quality assurance systems can balance (1) the need to increase access and availability of quality VPC seed for smallholders with (2) the need to minimize the biotic threats that accompany low-quality seed production, distribution, and use, this paper examines three questions. First, what types of public policies and regulations currently govern quality assurance in VPC seed systems? Second, how do these policies and regulations influence access, availability, and quality of VPC seed for smallholders? Third, what alternative strategies might be employed to increase access, availability, and quality of VPC seed for smallholders?[2]

Drawing on qualitative analysis of current policies and practices, we examine policy options for LMICs by exploring quality assurance regulations for four crop-country combinations: cassava in Nigeria and Vietnam, and potato in Kenya and Vietnam. The paper highlights both the theory and practice driving existing models of regulation; offers alternative models of VPC seed quality assurance systems; and recommends policy, regulation, and investment options for VPC seed markets. In doing so, it explores both farmer-based seed systems, commercial seed systems, and integrated seed systems that link key elements of both systems (Almekinders and Louwaars, 2002; Coomes et al., 2015; De Boef et al., 2010; Louwaars et al., 2013; Spielman and Smale, 2017).[3]

The paper makes a unique contribution to the literature on seed policy in LMICs by emphasizing a class of crops that are typically overlooked in the analysis, design, and implementation of seed regulations. The policy literature on seed systems has revolved almost exclusively around major cereals, and has neglected VPCs (Thiele et al., 2021; McEwan et al., 2015). In fact, we know of no policy studies on VPC seed systems in LMICs beyond those prepared for this study. The paper also makes a novel contribution by providing detailed recommendations that address the research questions set forth above and addresses specific gaps in VPC seed systems related to policy and regulatory options.

1.1. Background and context

The crop-country combinations examined in the study that underlies this paper were primarily chosen to provide variety in terms of crop uses in the economy (subsistence/consumption versus commercial/industrial use) and the nature of the crop seed systems (formal and regulated versus informal and unregulated). The VPCs and VPC seed systems are heterogeneous across both crops and countries: significant differences exist in crop reproductive biology, the material used for planting, each commodity's economic and cultural value, and the context in which they are cultivated, exchanged, processed, and consumed. The case selection captures several key dimensions of this heterogeneity, while also highlighting commonalities, with the aim of developing a methodology that can be applied to other VPC crop-country combinations and further enrich the research on VPC seed system policy and regulation. For details, see the complete country studies in McEwan et al. (2021) on potato in Kenya, Gatto et al. (2021, 2020) on cassava and potato in Vietnam, and Wossen et al. (2024) on cassava in Nigeria, and Spielman et al. (2021) for a cross-country synthesis.

1.1.1. Potato in Kenya

Potato in Kenya was chosen for its importance in the country's agricultural development strategy, its widespread consumption, its increasing use as a commercial/industrial commodity, and the near absence of a formal seed system (Okello et al., 2017; Harahagazwe et al., 2018; Laibuni and Omiti, 2014; Muthoni et al., 2013; Gildemacher et al., 2011; Muthoni and Nyamongo, 2009). In 2017/18, just three entities—one public and two private sector—accounted for more than 75 % of Kenya's certified seed potato production, but just 4–5 % of the estimated market for seed potato (Muthoni et al., 2013; Schulte-Geldermann, 2013; Tesfaye et al., 2010; Gildemacher et al., 2009). Most smallholders source seed from their own farms, from neighbors, or from market traders selling small ware potato as seed. These practices likely contribute to low seed replacement rates, low yields, and a high prevalence of seed- and soil-borne diseases—bacteria wilt, late blight, and potato cyst nematode (PCN) (Kaguongo et al., 2014; Muthoni et al., 2013; Gildemacher et al., 2009). Despite these challenges, the Government of Kenya has articulated plans to expand potato production area, volumes, and value, most recently in the 2016 National Potato Strategy, the 2017 Presidential Initiative on the "Big Four Pillars of Development", and the 2018 Agricultural Sector Transformation and Growth Strategy (GoK, 2018; GoK, 2017; GoK, 2016).

Kenya's seed sector is governed by the Seeds and Plant Varieties Act (1972) and its subsidiary regulations, guidelines, amendments, and revisions. The law clearly states that uncertified seed is illegal in Kenya: no one is permitted to sell seed of the species subject to compulsory certification ("Schedule 2" crops, which include potato), unless it has been certified or otherwise meets a minimum standard prescribed for the class and species. However, reality departs widely from written law. Not only do farmers buy and sell seed potato among themselves, but also nongovernmental organizations (NGOs), charitable foundations, and research organizations train farmers in the production and distribution of quality (but uncertified) "clean" seed potato.

Recent amendments to the Act (and related policies, regulations, and guidelines) aimed to align Kenya's seed policies more closely with international seed standards, domesticate regional obligations related to harmonized seed regulations, and reinforce the role of certified seed in addressing emerging pests and diseases, thereby encouraging private investment—particularly foreign private investment—into Kenya's seed sector.[4] Meanwhile, the country's new constitution in 2010 shifted a significant share of responsibilities for seed policy implementation from the central government to county governments; however, the Kenya Plant Health Inspectorate Service (KEPHIS) remains the country's autonomous regulatory entity in charge of seed certification and phytosanitation.

1.1.2. Cassava in Nigeria

Cassava in Nigeria was chosen based on the crop's central role in the

[2] In the context of this study, the term "strategies" is used to describe a set of actions undertaken by government agencies, seed providers, farmers, and other actors in a seed system. These strategies are, inter alia, informed by policies that define the goals, objectives, and priorities of a seed system and the actions that a government takes in support of that system; the regulations that set parameters for these actions; and investments that allocate public resources to these actions.

[3] Throughout this paper, we refer to "informal" and "formal" seed systems as shorthand for the extent to which seed quality is regulated. But this characterization may also be pejorative in that it incorrectly suggests that farmers in "informal" systems save and exchange seed within their communities or in local markets in an ineffective manner, while farmers in commercial systems exchange seed through more formal (i.e., a "better") channels. As such, we attempt to use these terms in a neutral, non-pejorative sense.

[4] Following the completion of this study, Kenya began a public consultation process to revise the regulations governing VPC planting material that would create more space for farmer-based seed systems to operate. The public consultations are a step toward approving, gazetting, and implementing new regulations.

country' successive agricultural development strategies, its widespread production and consumption, its linkage to value addition activities, and its reliance on informal seed systems. Nigeria is the world's largest producer of cassava, accounting for roughly 20 % of global production. Throughout much of the country, farm households produce most of the crop as a staple food and a source of income. Cassava is also an increasingly important feedstock in agro-industrial processing (Wossen et al., 2017; Alene et al., 2012; Dixon et al., 2011). Yet Nigeria's yields are at most half of the yields achieved in other major cassava-producing countries such as Thailand, Ghana, and Vietnam (FAO, 2020; Wossen et al., 2019).

About 70 % of all Nigerian cassava farmers report using own-saved stems or informally exchanged stems as seed, while 6 % report obtaining them from local markets and 17 % from semi-formal and formal sources such as government extension services, research institutions, and processors (Wossen et al., 2017). This raises concerns about the transmission of yield-reducing pests and diseases (Rabbi et al., 2015; Gibson et al., 2009).

Nigeria's seed system operates under the legal framework of the 1992 National Agricultural Seed Act (Decree no. 72). Subsequent amendments led to the establishment of the National Agricultural Seed Council (NASC), Nigeria's primary regulator for seed quality assurance.[5] But Nigeria's cassava seed system is distinguished more by projects than legal frameworks. Efforts to create a formal seed system date back to the 1970s, when the International Institute of Tropical Agriculture (IITA) and National Root Crops Research Institute (NRCRI) bred tropical manioc selection (TMS) varieties resistant to cassava mosaic virus disease (CMD), and large-scale distribution efforts were organized by government agencies, international development partners, and NGOs (Nweke, 2010). In the early 2000s, several programs furthered efforts to create a more formal cassava seed system the Root and Tuber Expansion Program initiated under the 2002 Presidential Initiative on Cassava and the Cassava Transformation Agenda of the 2011 Agricultural Transformation Agenda (Donkor et al., 2017). These initiatives prioritized the distribution of improved cassava varieties, pursued regulatory reforms in the seed system, and created incentives to stimulate private investment in processing. Later initiatives included the High-Quality Cassava Flour initiative and the Cassava Bread Development Fund, which aimed to increase demand for quality cassava as a feedstock for agroprocessing, and the Growth Enhancement Scheme, which subsidized distribution of improved cassava varieties (FMARD, 2014; Asante-Pok, 2013). More recent projects continue to distribute new varieties and clean planting material, with specific emphasis on commercializing elements of the cassava seed system.

1.1.3. Potato and cassava in Vietnam

In Vietnam, potato and cassava were chosen largely as a contrast to the Kenya and Nigeria experiences. Cassava is almost exclusively a feedstock to Vietnam's starch industry, not widely consumed as a food staple, yet still dependent on informal seed systems (Le et al., 2019). Between 2000 and 2016, cassava cultivation expanded from about 237,000 ha to a peak of 570,000 ha, while production increased from approximately 2 million tons to 11 million tons. This indicates that the more than doubling of yields is substantially attributable to the introduction of high-yielding varieties (FAO, 2020; Le et al., 2019; Labarta et al., 2017). In 2016, 70 % of the country's cassava production was exported as starch or chips for use in processed food, animal feed, pharmaceutical, and industrial alcohol production (ITC, 2018). These exports—88 % of which were destined for China—generated over US $700 million in revenues. The cassava seed system that fuels this industry is almost entirely informal: as of 2016, 90 % of cassava farmers obtained their initial planting material through informal exchanges (Le et al., 2019).

Potato, however, is of marginal importance in Vietnam—neither widely produced in large quantities nor consumed as a staple. Yet the crop is increasingly important to Vietnam's agroprocessing industries, the urban commercial food sector, and international trade considerations, which, in turn, may lead to an increasingly formal seed system. Since the mid-1980s, cultivated area has stagnated at 20,000 ha, and production at about 300,000 tons (FAO, 2020), despite increasing demand from consumers and food processors that has led to sizable increases in imports. Between 2001 and 2016, potato imports, primarily from China, increased from 1574 to 39,700 tons (ITC, 2018).

Vietnam's seed potato system is relatively formal. In 2016, Vietnam imported 3650 tons of seed potato from Germany, Korea, China, Netherlands, and Canada. A significant share of these imports is likely further multiplied domestically, while additional but unknown quantities of seed may also come from China in the form of small ware potato.

For both crops, Vietnam's seed system is governed by laws and regulations established in1996 (Decree No. 07/1996/ND-CP) and focused mainly on varietal improvement, seed quality, and rapid multiplication. Only certified seed may be legally traded, and the production and trade of "fake seeds, seeds of poor quality, mixed seeds, seeds with pest or disease germs or seeds which have not been certified" is forbidden (Article 13, Decree 7/1996). Subsequent legislation provides guidance on seed production, quality standards, plant variety protection, and other essential elements of a robust seed system. Yet the Vietnam Ministry of Agriculture and Rural Development (MARD) also issued Decision 35/2008/QĐ-BNN in 2008 that explicitly permits farmers to collect, store, preserve, use, and distribute local plant varieties and genetic resources, and makes farmers eligible for public financial support for seed production activities (Tin et al., 2011). Although this decision still precludes farmers from engaging in commercial seed activities, it recognizes the informal seed sector (Lua et al., 2015), and thus implicitly acknowledges that many farmers engage in local-level commercial seed exchanges with fellow farmers.

2. Methods

Data and information were collected from multiple sources: key informant interviews (KIIs), focus group discussions (FGDs), publicly available documents, and secondary household and market data. While the study is primarily a qualitative investigation, it did draw on quantitative data to augment and validate its findings.

KII and FGD participant selection was guided by the multi-stakeholder framework for research on root, tuber, and banana seed systems (RTB, 2016; Bentley et al., 2018). Interview topics were similarly selected based on this framework, and were further informed by seed system context analysis, a review of relevant policies and regulations, and secondary data on seed use, sources, and pricing.

A total of 95 semi-structured interviews involving 241 individuals were conducted (Table 1). Participants were interviewed in 2017 using semi-structured interview guides developed for each category of actor; see IFPRI et al. (2019) for the interview guides.[6] The guides covered topics ranging from basic details about the respondent and their role in seed production or use, to their understanding of VPC quality assurance

[5] The Act was replaced by the new 2019 Seed Act, which came into effect in May 2020, after this study was conducted. The 2019 Seed Act includes several significant changes: recognition of third-party certification, increased penalties for counterfeiting, and recognition of propagation materials as "seed" for certification of VPCs.

[6] It is worth noting that seed users (farmers) did not figure prominently among these respondents. Farmers were interviewed in each country about their seed sources, uses, and preferences; however, a strict sampling procedure was not followed because the scale required for unbiased sampling of farmers for each country-crop combination exceeded available resources. Thus, we do not highlight findings from our farmer interviews and instead rely on secondary data wherever possible.

Table 1
Organizations and individuals interviewed, by country.

Classification of interviewed organization or individual	No. of interviews conducted							
Category	Kenya		Nigeria		Vietnam		Total	
	Org	Ind	Org	Ind	Org	Ind	Org	Ind
1. Policymakers, advisors, and regulators	5	14	4	28	5	17	14	59
2. Public research agencies, institutes, centers, and stations	4	11	7	67	5	13	16	91
3. Individual and small-scale seed entrepreneurs and enterprises	6	18	41	41	6	7	53	66
4. Private companies and industry associations	9	15	1	8	2	2	12	25
Total	24	58	52	77	18	39	95	241

Note: "Org" denotes organizations and "Ind" denotes individuals that participated in key informant interviews or focus group discussions for this study.

standards and practices, views on current policies and regulations, and insights on impacts for female and male seed producers and users. Respondents were selected using a combination of purposive and snowball sampling methods, focusing on individuals and organizations relevant to critical components of the seed system, such as seed availability, access, and quality.

Respondents included individuals and organizations drawn from the following populations: public and private sector scientists and technicians working on breeding high-quality planting material of VPCs; public regulators who design, supervise, and/or manage quality assurance systems for VPC planting materials; industry experts and industry association representatives who are engaged in regulatory issues related to VPCs; and entrepreneurs, business people, traders, seed importers, non-governmental organizations, or other individuals who conduct business in the production, distribution and/or marketing of VPC planting material. Their selection was informed by literature review, context analysis, and stakeholder mappings. The number of interviews varied by country and crop, depending on the size and complexity of the seed system (see Table 1). Because KIIs and FGDs are susceptible to several types of bias (e.g., sampling, location/placement, and social desirability bias), concerted efforts were made to employ best practices in qualitative data interpretation and analysis. For details, see the related studies by Spielman et al. (2021), McEwan et al. (2021), Gatto et al. (2021, 2020), and Wossen et al. (2020, 2024).

To complement the interviews, a range of documents were collected and analyzed, including legislative documents, regulatory handbooks, technical manuals, project reports, research papers, economic and agricultural statistics, and other documents relating to agricultural development policy, seed systems regulation, and related issues. Many of these were collected from government agencies and websites, although material was also gathered from donor agencies, international organizations, NGOs, and companies.

Several qualitative methods were used to analyze the data and build framing narratives, all of which draw on methods and tools of policy analysis (e.g., Sabatier, 1988; Roe, 1994) and applied to agriculture (e.g., Mockshell and Birner, 2020; Scoones, 2005) and seed sector development (e.g., Scoones and Thompson, 2011). Thematic analysis was employed to identify recurring themes and patterns in the interview transcripts, highlighting key issues and insights. Framework analysis was also applied, organizing the data into predefined themes based on the multistakeholder framework used in the study We focus more on grounding and analyzing the data and information extracted from these methods, and less on the formal application of these methods using specialized software for data management or analysis. Taken together and by drawing on the multistakeholder framework (RTB, 2016; Bentley et al., 2018), this approach provides us with the analytical space needed to compare and contrast the interests and roles of various actors in relation to policy and regulatory interventions across our different crop-country combinations.

3. Results

Our main results are presented here as framed narratives that result from our analysis of the semi-structured interviews, document analysis, and secondary data, as detailed above. First, we compare and contrast VPC seed systems across our crop-country combinations to illustrate both the diversity and generalizability in our analysis of seed quality assurance. Second, we examine a set of seed quality assurance strategies commonly employed across the crop-country combinations. Third, we examine the form of seed quality assurance strategies in the context of each country's broader strategic frameworks for growth and development. We look specifically at the contested narratives and actor coalitions that form around these narratives. Finally, we discuss the potential impact of these regulatory strategies, narratives, and coalitions on the access to and availability of quality VPC for smallholders in the focal countries.

3.1. Seed system variation and generalizability

Our findings indicate significant cross-country variation in terms of the role, authority, and autonomy of the regulatory body; the relative influence of actors on the seed system and its regulatory functions; and the degree of integration between formal and informal seed systems. Variations also exist in the crops' value in terms of production and consumption, and the crops' role in a country's economic growth, trade, and agricultural development strategies and policies. Despite the variation across the crop-country combinations, we also observe several generalizable attributes.

Each country has a coherent legal framework and regulatory structure governing the seed system; a research system that breeds new varieties; a regulatory body that certifies seed; some combination of public and private seed producers; public agencies, public programs, private companies, and other entities that distribute seed to farmers; widespread farmer seed savings and farmer-to-farmer seed exchanges; and market-based seed exchanges. Fig. 1 provides a schematic of how VPC seed systems function, drawing on these commonalities and focusing primarily on the flows of material between actors and associated regulatory functions. The diagram highlights the multiple seed distribution channels: state-owned producers, public distribution programs, and farmer-based organizations; domestic and foreign firms; and traders, retailers, and entrepreneurs of varying sizes and scales. It also shows the various qualities of seed distributed, ranging from early generation seed used in breeding programs and research centers, to certified or quality declared seed that is approved by regulatory agencies, to seed saved and exchanged by farmers themselves. Finally, the figure highlights farmers' diverse contributions to seed production and use—as contract seed multipliers, commercial producers in their own right, conservators of genetic diversity, and seed users.[7]

Although the actors, functions, and relationships shown in the figure may not be present in each of our crop-country combinations, The figure illustrates complex nature of the relationships within VPC seed systems, including interactions between formal and informal systems (Louwaars

[7] Note that for simplicity, Fig. 1 does not highlight informational flows or informational feedback loops on, e.g., farmer feedback to breeding programs on their preferences for specific traits. These informational aspects of a seed system are nonetheless important to its performance and development.

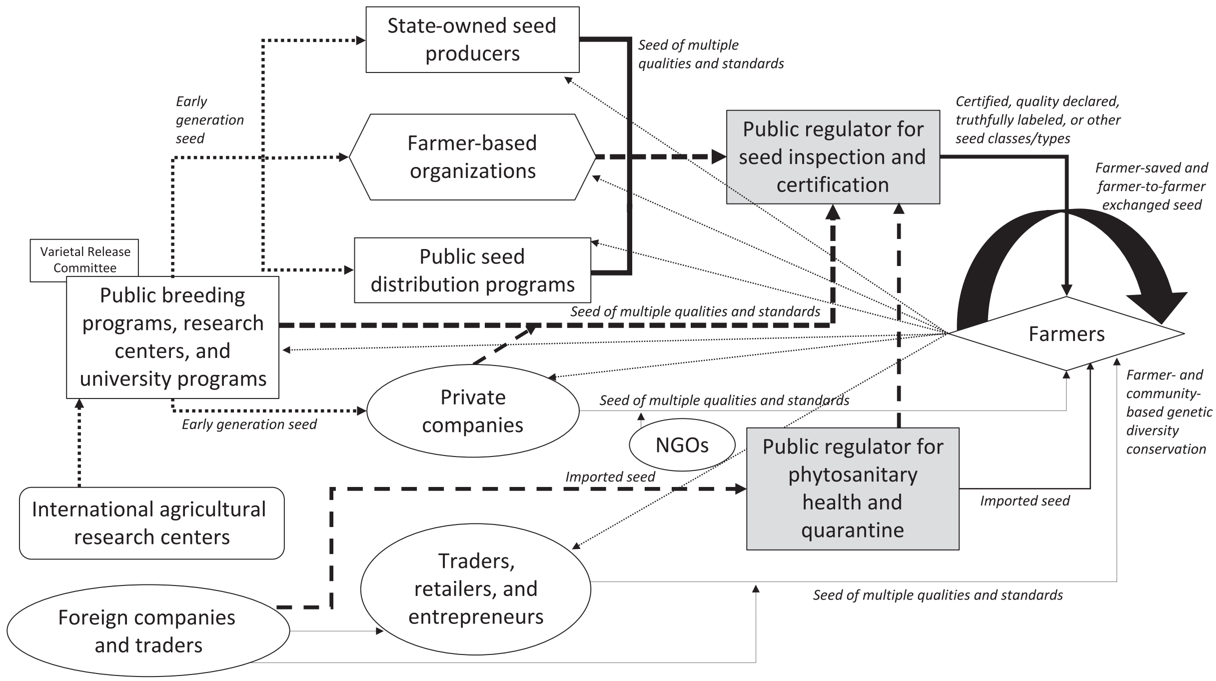

Fig. 1. A generalizable schematic of seed systems for vegetatively propagated crops across the four crop-country combinations.
Note: Solid lines denote seed used in cultivation; the weight of each line indicates notional volumes of seed moving through the indicated channel; dashed lines indicate regulatory channels; smaller dotted lines indicate channels for early generation seed movement; and the smallest dotted lines indicate farmer production and supply of seed that is meant for seed providers. Gray boxes are regulatory bodies. Rectangular, trapezoid, and circle shapes indicate public, civil society, and private organizations, respectively, while the diamond shape indicates farmers.

et al., 2013; Almekinders and Louwaars, 2002), and can help in identifying intervention points for inducing change.

3.2. Regulatory diversity and commonality

Five strategies for regulating VPC seed systems are common across all our crop-country combinations. We describe each in detail below.

First, breeding programs and research centers engage directly in seed production, distribution, and quality assurance, the latter occurring most often because of insufficient regulatory system capacity. In Nigeria, for example, the national research system breeds CMD-resistant cassava varieties *and* plays a primary role in their distribution. Similarly, in Vietnam, the public research system distributes quality seed potato and CMD-resistant cassava varieties; and in Kenya, the country's potato breeding program is investing in the development and distribution of biotic stress-resistant varieties. Of course, seed health—specifically, the health of early generation seed, which is often the first line of defense against seed- or soil-borne pests and diseases—is a core function of research and breeding programs. However, large-scale production, distribution, and quality assurance typically lie outside their mandates, comparative advantages, technical capacities, and budgets.

Second, seed system actors aim to promote good management practices to smallholders for the preparation of own-saved seeds and small-scale seed production enterprises. In Kenya, for example, seed potato projects organized by NGOs train village-based extension workers and self-help groups in seed potato production, and in Nigeria, village seed entrepreneurs are trained in cassava stem multiplication. Notably, government agencies—county agricultural extension services in Kenya, state agricultural development programs in Nigeria—participate substantially in these projects despite regulations that discourage small-scale production of non-certified seed for both crops. In these cases, the exigencies of market demand and project funding may simply outweigh regulations, leading to tacit state recognition of the informal VPC seed system. In Vietnam, there seemed to be less emphasis on smallholder engagement but a similar level of pragmatism and tacit recognition of informal systems. In all cases, the cost-effectiveness and sustainability of this strategy remains uncertain.

Third is the policy and practice of quarantining, destroying, or otherwise removing crops acutely infected by pests or diseases. This reactive strategy is prominent in Vietnam, where the government monitors pest and disease (P&D) outbreaks as well as potentially contaminated seed lots, and destroys infected and quarantined cropland. This strategy was used in Vietnam's response to the CMD outbreak and to ware potato of potentially low quality imported from China and used as seed. But it is less common in Kenya and Nigeria: we found no evidence of measures taken at the same scale as was found in Vietnam.

Fourth, countries may rely on imports to ensure farmers have access to quality seed. Vietnam relies on imports of certified seed potato from European and other countries where high-quality material is commercially available, particularly for varieties used in food processing industries. In effect, Vietnam recognizes its comparative disadvantage in seed potato production, and so relies on imports of quality seed, going as far as subsidizing these imports. This strategy also permits public or private sector efforts to improve the quality of domestic seed. However, non-certified or substandard materials may also be imported through other channels, such as the cross-border trade in ware potato with China. Kenya, which similarly imports certified seed from Europe, has taken the opposite approach on occasion, rejecting the quality assurances provided by European seed potato producers.

Fifth, formal inspection and certification of seed is conducted by all three countries. Kenya's seed regulator, KEPHIS, is arguably the most effective, yet its capacity to monitor, inspect, and certify VPC seed production is limited, cover inspection of seed potato production only in the small formal potato sector. KEPHIS has neither the resources nor personnel to monitor and inspect small-scale seed potato producers, despite the recent decentralization of inspection offices in major ware production areas and the use of private accredited inspectors. Nigeria's capacity was even more limited, and Vietnam's varied between regions and crops.

Each of the five seed quality assurance strategies described above is associated with a particular set of costs and benefits. Fig. 2 provides a stylized mapping of these strategies in terms of the value provided (effectiveness in combatting P&D pressures) against the public expenditure requirements (for research, extension, and regulation). On the cost side, both inspection of seed imports and quarantining/destruction of affected standing crops cost more than breeding or extension programs, particularly when measured in terms of the cost per unit of seed produced, and especially when accounting for the broader economic and social consequences of a quarantining/destruction strategy, as in Vietnam.

In terms of capacity to address P&D pressures, certified seed imported from countries with highly effective regulatory systems might seem like an effective means of combatting these pressures, but experiences in Kenya and Vietnam suggest the opposite, as pathogens may have been introduced through these import channels. Thus, national breeding for host resistance and other science-based strategies such as biological control systems are potentially more effective.

Furthermore, these strategies may be close substitutes or complements. For example, a strong breeding program for disease-resistant varieties can reduce the need for costly and recurring quarantine strategies or seed certification systems. Other strategies, like better crop management practices, are complementary to breeding, as they address challenges that breeding alone cannot fully resolve, e.g., seed-borne pathogens. And from a temporal perspective, while breeding for host resistance functions primarily as a long-term, proactive strategy that lowers pest and disease pressure over time, strategies such as quarantine or pest management are complements in so far as they provide short-term, reactive measures to address immediate outbreaks or high-pressure situations.

Relatedly, the three countries all employ multiple strategies. Kenya's approach includes a research system and regulatory agency that together work well in supplying quality seed potato and managing P&D pressures (albeit within a small commercial market). Nigeria's research system, extension programs, development projects, and government initiatives have shown similar levels of effectiveness. And Vietnam's "quarantine and destroy" strategy, while draconian, is offset by its openness to seed imports. In sum, seed quality assurance systems for VPCs cannot rely exclusively on a single strategy: seed quality regulations, public investment in research and extension, accommodating trade policies, and active surveillance of plant health all have a role to play.

Finally, and somewhat problematically, we find that these strategies are often derived from strategies for cereal seed quality assurance. For example, the amendments made to Kenya's seed regulatory framework reflect quality assurance requirements for maize, rather than VPC seeds, which face problems of inter-seasonal storage and centralization of production. As a result, references in the amendments—such as to seed lots, germination tests, inspection frequency, and sampling schemes—are appropriate to cereals but less so to potato and other VPCs; and limits on the number of allowable generations from breeder to certified seed are not applicable to potato which, as a clonally propagated crop, is less prone to genetic erosion. Moreover, on the implementation side, there are reports of arduous and costly procedures and lengthy delays for registration and inspection coupled with limited capacity of the seed regulators, who are more familiar with cereal crops, to work with VPCs. These realities discourage potential entrants to seed production, particularly smallholders, and pose challenges for seed inspection and certification.

3.3. Competing narratives and actor coalitions

Competing narratives were found around the role of policy and regulation in VPC seed sector development. While assessing the relative power of these competing narratives is difficult, we look at the main narratives and the actor coalitions behind them in our crop-country combinations.

The primary narrative across all three countries frames seed system concerns in terms of "food security first." In Kenya, the current strategy for economic growth and agricultural development—the "Big Four" agenda and the ASTGS—view seed primarily through a food security lens. This means prioritizing seed policies, regulations, and investments that close yield gaps, increase crop production, and reduce food prices to ensure affordable food staples for the country's growing population. As a result, many line ministries and agencies involved in agriculture view seed systems as a vehicle to provide farmers with affordable access to improved varieties and quality planting material. The narrative is similar in Nigeria, but less so in Vietnam, given that cassava and potato are not considered essential food crops.

The result of putting food security first is that short-term increases in seed supply to increase food production often outweigh longer-term improvements in seed market functioning, rural enterprise development, and regulatory coherence. Public investment in seed production, distribution programs, and state-owned enterprises is rationalized even if it crowds out farmer-based and private-sector providers. It also favors the short time horizons of most political leaders and their preference for immediate observable results.

Another dominant narrative shared across all three countries frames VPC seed sector development in terms of "regulation first" or "pest- and disease-risk mitigation first." It emphasizes the need to regulate quality more effectively to ensure seed producers and retailers provide quality seed to farmers. In Kenya, many key informants argued that only certified seed potato could prevent the spread of pests and disease and protect national potato production and yields. But supporters of this narrative rarely recognize that demand for seed far exceeds the regulators' capacity to inspect and approve seed for sale in sufficient quantities. Insufficient quantities of certified seed may result in scarcities or higher seed prices and cause farmers to rely on saved seed, which contributes to P&D pressures and, ultimately, low yields and output.

Another narrative suggests that quality assurance regulation and enforcement is essential to encourage private investment in a country's seed market. This "private investment" framing is most apparent in Vietnam, and in Kenya, where it is split between "foreign private investment" and "domestic private investment." The first is characterized by foreign firms seeking plant variety protections and easy navigation through phytosanitary inspections and quarantines for imported seed, or seeking inputs for vertically integrated production systems (namely potatoes for chips and fries in their food outlets). The second is characterized by domestic seed producers seeking more efficient, lower-cost inspection and certification procedures and, in certain instances, infant industry protections from foreign competition, as well as vertically integrated agroprocessing firms.

The final narrative, which emphasizes "grassroot development," is closely related to both the "food security" framing and the "integrated seed sector" framing discussed at the outset of this paper. It holds that non-certified, farmer-managed production of "clean" seed is feasible; that pragmatic, decentralized alternatives to a strict regulatory system exist; and that yield gains will contribute to improvements in rural livelihoods over a longer period than the timeframe of interest to policymakers or regulators. The village-level models for cassava seed production in Nigeria and seed potato production in Kenya are useful examples. These efforts hinge on investments in technical capacity and strong self-regulation to encourage growth of local VPC seed systems and markets.

In each country, the actor coalitions and networks that subscribe to these narratives are fluid, as is the distribution of power among them. For example, in both Kenya and Vietnam, there is a strong coalition around private investment in their seed sectors, including foreign and domestic interests and policymakers. The revisions to Kenya's seed regulatory framework since 2010 reflect this in their strong focus on increasing private foreign and domestic seed sector investment (also see Munyi and De Jonge, 2015). Yet these coalitions are fairly tenuous. In Kenya's potato sector, bilateral development agencies support their

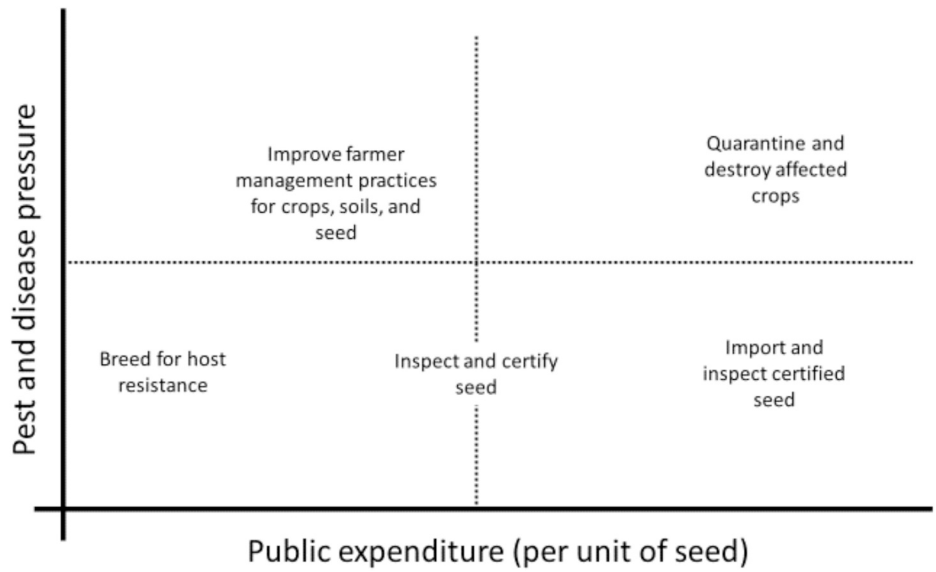

Fig. 2. A stylized[11] mapping of VPC seed quality assurance systems against pest and disease pressures and public expenditure requirements.

private sector counterparts to advance plant variety protection legislation and guidelines, strengthen regulatory standards and capacities, and increase the availability of varieties and seed for potato used in processing and food retailing. Yet this same coalition does not exhibit much interest in the efficiencies associated with competitive markets; rather, it is aiming to secure market power and advance political interests through favorable policy and regulation, often pitting itself against organizations dedicated to developing more local, farmer-based seed systems.

Moreover, there are significant absences in these coalitions, contrary to the growing body of theory and evidence suggesting that technological change at the farm level will be driven by demand from actors further along the value chain (e.g., Reardon and Timmer, 2012). For example, in the case of cassava in Vietnam, starch factories play little role in the provision of improved varieties or quality seed to farmers who supply their feedstock. Similarly, in Nigeria, enterprise development initiatives meant to increase cassava's use in processing and food preparation have had little influence on either varietal change or seed quality assurance systems. This may reflect several factors, for example, the nascent development of the industrial starch and gari processing industries, they may not be concerned about the quality of their feedstock. Or it might reflect a strongly segmented market in which value chain actors have little influence on seed quality among smallholders, who cultivate varieties that are preferred for home consumption rather than by commercial operations. Or it may be that the varieties in use are either resistant to major pathogens affecting seed, or the pathogens are not particularly problematic to farmers or other value chain actors.

We also observe that governments—policymakers, public researchers, and regulators—do not necessarily play the role of "benevolent social planners" or present themselves as a single actor-coalition. In each crop-country combination, government actors subscribe to one or several of the narrative framings above, and participate in coalitions to advance the associated narrative. In Kenya, divergence is observed between policy actors and regulators, the former advancing a strong "food security" narrative and the latter advancing a clear "regulation first" narrative. In Nigeria and Vietnam, regulators and policy actors alike take a pragmatic perspective—acknowledging that regulation of the entire seed system is nearly impossible.

Lastly, we observe that national advocacy groups—the seed trade associations and crop grower associations—play a limited role, and rarely provide effective representation of farmers, whether as producers of seed or crops. In some instances, they are merely extensions of government or donor interests. In others, they represent just a sub-set of private sector interests—foreign or domestic. That said, we note some fairly active advocacy groups in Kenya, each working within one of the many coalitions, and several are contributing constructively to the design and formulation of seed regulations through various stakeholder engagements. However, national research organizations and policy think tanks show little leadership in providing data and analysis to inform these debates and guide VPC seed regulatory reform, with the possible exception of Kenya where several domestic and foreign organizations engage actively.

3.4. Drivers of change: organizations, technology, trade, and crisis

Extending this analysis of competing narratives and actor coalitions, we identify several key drivers that affect policy, regulation, and, ultimately, the potential for VPC seed market growth in our crop-country combinations. We examine (1) institutional factors and organizational innovations; (2) technological opportunities; (3) emerging market and trade factors; and (4) the effect of crises and related responses.

In terms of institutional and organizational factors, the role of the state's regulatory apparatus emerged as the most significant factor. KEPHIS in Kenya, NASC in Nigeria, and MARD in Vietnam embody the states' regulatory power. Although they operate quite differently—each with distinct levels of independence, autonomy, coverage, and technical capacity—the rules, guidelines, and procedures they are charged with executing play a fundamental role in shaping the market for VPC seed. These institutions have introduced several simple innovations with potentially far-reaching regulatory consequences. For example, KEPHIS adapted its regulatory infrastructure to the constitutional devolution of administrative powers, allowing the regulator to extend its reach and to support county-led initiatives in seed production and distribution. KEPHIS is also managing the introduction of accredited private seed inspectors, with the first inspectors drawn from seed companies and trained to operate their companies' internal quality assurance practices in compliance with KEPHIS standards. Use of accredited private inspectors could extend the reach of inspection agencies that are otherwise hobbled by limited personnel and infrastructure, although concern remains about potential problems in the absence of sufficient oversight.

On the technological front, efforts are underway to develop and scale new seed multiplication systems, including rapid propagation techniques such as aeroponics for mini-tuber production and transplanted tissue culture plantlets for production of rooted apical cuttings. These technologies could transform the commercial viability of VPC seed systems, and require regulators to change their standards and guidelines (Demo et al., 2015; Parker, 2019; Parker et al., 2019). Low-cost field disease diagnostic kits may soon improve the accuracy and timeliness of inspection procedures, while seed tracking/traceability systems may increase user confidence in seed quality. While these technologies have yet to be rigorously evaluated, their potential appears considerable.

Trade considerations are also driving change. Regional harmonization of seed regulations in eastern and southern Africa under COMESA, and in western and central Africa under ECOWAS, offer Kenya and Nigeria opportunities to expand their VPC seed products into neighboring countries, subject to a well-defined quality assurance system. Vietnam is also attuned to trade considerations, although as a full-fledged member of the World Trade Organization and a strongly export-oriented economy, its primary concerns involve phytosanitary standards for imported seed. In all three countries, compliance with the global trade regimes governing the seed industry seems to be at the forefront among policy considerations.

Interestingly, as discussed above, industry and demand-side factors appear to play a very marginal role in driving more effective VPC seed quality regulation. For example, fast-food retailers in Kenya and Vietnam, who might be expected to demand a regulatory system that ensures a steady supply of quality planting material for varieties suitable for potato chip production, have exerted surprisingly little pressure on regulators. In Kenya, neither KEPHIS nor the wider potato production system have been influenced by this "demand-pull" effect, likely because fast food remains a small niche in the larger potato market. The absence of this effect is more striking in Vietnam, where starch factories play no role in ensuring farmers can meet their specific feedstock requirements.

In fact, crisis is the most common driver of change observed in our crop-country combinations. The outbreak of a pest or disease tends to marshal significant regulatory responses. In Kenya, crises have included the spread of bacterial wilt and PCN for potato; in Vietnam, an outbreak of CMD for cassava and the import of poor-quality potatoes used for seed; and in Nigeria, the persistence of CMD. In each country, these threats led to different responses. Vietnam pursued its "quarantine and destroy" strategy. Kenya doubled down on its zero tolerance thresholds for infected planting material, with minor impact on the informal seed production system. Nigeria opted for pragmatism. Given the seemingly intractable challenges of regulating a cassava seed sector that easily reverts to an unregulated state, Nigeria's seed system actors have allocated quality assurance strategies to researchers, technologists, and entrepreneurs. This pragmatism is implicit in the other crop-country combinations, where there is tolerance—and even active support—for informal seed systems.

That does not mean that VPC seed systems escape regulatory scrutiny entirely. In Kenya, regulators and administrators at multiple levels have learned valuable lessons from experience in maize sector about how to control the proliferation of low-quality or fraudulent seed, and seem keen to apply those lessons to other crops and markets. And in both Kenya and Nigeria, pressures from the regional harmonization of seed regulations and regional trade integration may be causing these same regulators and administrators to take trade-related seed quality assurance matters more seriously. But it remains to be seen whether prior experience with cereal crops and trade concerns will accommodate the unique characteristics of VPC seed systems and seed quality issues.

4. Discussion

Given these findings, what are the options for improving policy and regulation for quality VPC planting material and increasing availability of and access to quality seed? We begin with several important caveats. First, each crop and its seed system are context-specific, meaning that options that work in one market, agroecology, or country may need to be adapted to fit another context. Second, policy and regulatory reforms are not necessarily win-win solutions: gains for one actor in a seed system may come at the expense of others. However, because the benefits from the current seed systems in the crop-country combinations are extremely limited, the policy options we propose assume that any expansion in seed market size will be welfare-improving, especially for smallholders. Third, policy change processes require political will, which is itself a function of how actor coalitions compete or cooperate in the policy and regulatory space. We recognize that these forces will play a key role in the success or failure of the policy, regulatory, and investment options explored below.

What type of policy and regulation is required for VPC seed quality assurance in LMICs like those in our study? We argue that a strict certification regime modeled on cereal seed certification regimes is inappropriate. The core issue here is not so much about crop reproductive biology (whether open-pollinating, self-pollinating, or vegetatively propagated), but rather the tendency to model VPC seed regulations after those designed for cereal crops. In many of the countries and crops we studied, stringent cereal seed quality regulations (especially for hybrid maize) are viewed as the gold standard, and efforts are often made to replicate similar standards for other crops. This approach is akin to designing national road and highway regulations solely for trucks, even though the roads are also used by cars and motorcycles. Instead, broader consideration is needed, taking into account factors beyond reproductive biology, such as market signals, transport infrastructure, farmer profiles, regulatory capacity, and farmer capabilities. This suggests the need for very crop- and context-specific policy and regulation for seed quality assurance.

We observed both little articulation of demand for quality seed from farmers, industry, or consumers, and little capacity to supply regulatory services—either by an external public regulator or by practices internal to the firm or producer—in the fragmented markets for VPC seed. This does not imply that there is no demand for quality seed among smallholders, or that LMICs should dispense with VPC seed regulations. Rather, scarce public resources should be concentrated where they can have the most significant impact on seed quality. The options outlined below highlight a suite of policy, regulatory, market, and technological recommendations, although we avoid providing a ranking of options.

At the broadest level, our findings suggest that national policies should reduce the marginalization of informal VPC seed systems, as well as the strict limits on who can legally produce and distribute VPC seed. A more progressive policy regime—that recognizes existing informal seed systems and acknowledges the need to professionalize VPC seed providers with technical and financial support—would step back from the rhetoric of the more contested and controversial narratives described earlier. Of course, changing the language in policy documents may be merely a *de jure* remedy with negligible impact on *de facto* seed systems. But it may create a more permissive environment for public investment and regulation and support the development of VPC seed markets.

Our findings also suggest that regulations that introduce multiple seed classes accessible to farmers, rather than a single class (i.e., certified), would potentially increase access by making different seed quality levels at different prices. This includes farmer-oriented quality-declared and quality-assured seed classes. This approach accommodates farmers who may not be able to afford the highest-quality certified seed but still want better options than own-saved seed or seed of unknown provenance. However, the success of this approach depends on balancing

[1] We refer to "seed systems" throughout this paper as a generic phrase to describe any system in which planting material is produced, exchanged, and used. This system covers true biological seed as well as asexually, clonally, or vegetatively propagated materials. For the purposes of this paper, cassava "seed" refers specifically to propagation material derived from stems or stakes cut from a mature plant, while for potato, the term refers to seed tubers used for planting. A "seed sector" refers to the set of seed systems that make seed available and accessible to farmers, and "seed quality" describes the characteristics that define the use value of a seed, including genetic, physiological, health, and physical attributes.

several trade-offs between seed market expansion, on the one hand, and consequences such as the yield penalties that may result from the use of lower quality seed or higher costs associated with monitoring quality for multiple classes.

Regarding public investment prioritization, more public resources should be invested in strengthening quality control and quality assurance for early generation seed production, that is, in the seed classes produced by research centers, private firms, and NGO that are used to produce the subsequent generation seed that is sold to farmers (Maredia and Bartle, 2022). These include mini-tubers and rooted apical cuttings produced using more cost effective and rapid multiplication technologies. This approach would not completely eliminate P&D threats but could reduce them. Importantly, the approach permits farmers, farmer organizations, and other actors to become producers of seed, at a higher level of quality than they would produce using their own material. It is a pragmatic option that may dissatisfy some pathologists and regulators, but recognizes the limitations of both formal and informal seed systems. This approach requires considerable investment—both public and private—in traceability systems for seed, multiple or complementary seed quality categories, and good seed production practices, which we explore below.

Traceability potentially allows supply chain actors to track seed back to its source, isolate supply chain nodes where P&D threats might have emerged, and take remedial action. Traceability systems can also support monitoring of varietal adoption and quality seed use—an important but still elusive means of measuring the impact of public investment in agricultural research and extension (Wossen et al., 2019; Kosmowski et al., 2019; Floro et al., 2017; Bold et al., 2017; Maredia et al., 2016; Rabbi et al., 2015). These systems range from simple paper-based tagging systems that designate origin, source, or permissible distribution areas, to more sophisticated tools such as blockchain. There are, however, potential limits on traceability where the purchase of planting material through formal channels (where traceability systems are installed) is infrequent due to low replacement rates.

Importantly, traceability systems are only as good as the seed producers that manage them. For many VPCs, those seed producers are likely to be farmers or farmer-based organizations serving their immediate localities, given the bulkiness and perishability of most VPC seed. Developing the capacity of these seed entrepreneurs and farmer-based organizations may be the most important investment for accelerating growth of VPC seed markets that serve the needs of smallholders (Maredia and Bartle, 2022). Their capacity needs range from training in seed production, identification and management of pests and diseases, and proper storage and packaging of seed, to business skills and enterprise development. Such capacity development efforts may be complemented by targeted subsidy programs that lower production costs for these small seed producers, improve the viability of commercial seed distribution networks, or encourage farmer uptake of quality seed. Note, however, that experiences with both producer and consumer (farmer) subsidy programs for seed sector development have been very mixed at best, across both crops and countries.

The success of such capacity development projects and subsidy programs ultimately depends on the signal associated with their products. Establishing a system of multiple quality standards can play a vital role in providing information to farmers and creating trust and reputational integrity for these producers over the long term. Multiple standards imply a combination of internal quality assurance practices, branding, packaging, and labeling by the producer itself; it also requires signals of external quality assurance, for example, quality declared or assured seed tags that indicate compliance with a more farmer-appropriate standard than certified seed standards. (See FAO (2010) for protocols and standards for quality declared planting material for VPCs.) In several of the crop-country combinations studied, the absence of multiple standards—indeed, the illegality of certain standards and practices—suggests significant opportunity for policy reform to increase the supply of quality planting materials (Maredia and Bartle, 2022).

The introduction of multiple classes or categories reduces entry barriers to the VPC seed market and allows seed producers to pursue marketing strategies such as product differentiation and price discrimination, provided, of course, that different seed systems are themselves recognized a priori. These factors, in turn, may encourage growth in the market for VPC seed and the growth of markets for specific niches—specific farmer typologies, agroecologies, and product attributes. This outcome hinges on sufficient supply of early generation seed, regulatory capacity to certify this seed, and investment in farmer entrepreneurs and farmer-based organizations.

This strategy of introducing multiple seed categories—and thus encouraging the growth and expansion of VPC seed markets for smallholders—is partly built on accelerated varietal turnover. In many smallholder systems, demand for fresh seed will remain inextricably linked to demand for new varieties embodying new biotic and abiotic resistance traits, processing or consumption qualities, or other characteristics. World over, varietal turnover is generally slow for VPCs, and farmers may only consider new seed if they are looking for new varieties with preferred traits. A continuous stream of improved varieties distributed as quality seed may be more marketable than simply quality seed. This approach has merits, but if the phytosanitary quality of VPC seed deteriorates faster than its genetic quality, then the acceleration of varietal turnover is unlikely to be a practical strategy (also see Thiele et al., 2021). Where low varietal turnover rates and unanticipated biotic stresses are common, a strategy that combines promotion of quality seed management practices to farmers with periodic replacement with disease-free seed may be more viable.

Given that the introduction of multiple seed categories is only as good as its implementation, our findings suggest a need for greater devolution and decentralization of regulatory processes at the local level. This means combining internal quality assurance systems of the seed entrepreneur or farmer-based organization with both (1) external oversight or audit function by the regulatory body, representing the supportive function (or credible threat) of external inspection of fields, plants, packaging, or records that limits rent-seeking behavior, and (2) technical support, training, and communication from those same bodies in building organizational capacity to meet regulatory expectations. Given the localized and dispersed nature of VPC seed markets, this requires some decentralization of the public regulatory apparatus and/or accreditation of private or public local administrators for oversight of agricultural development activities and programs.

The success of this strategy also hinges on investment in better mechanisms to assess, revise, and communicate risk to farmers and other seed system actors. New and emerging pests and diseases are a constant threat to VPCs, and responses to those threats can often be effectively coordinated through a well-integrated seed quality assurance system. The system described above attempts to provide such integration by professionalizing the seed system—in effect, formalizing the informal system while simultaneously informalizing the formal system (see Rana, 2010). However, an integrated system also requires, inter alia, more effective procedures for identifying both local and transboundary threats in a timely manner; better risk assessment standards that are strictly based on science and not simply on zero tolerance thresholds; greater capacity to conduct risk assessments, including assessments of social and economic risk; and better methods to engage with and communicate risk to farmers, farmer-based organizations, consumers, and other seed system actors.

There are also potential gains to be made from engaging in regional and global agreements that seek to harmonize seed quality regulations and encourage trade in quality seed. Regional harmonization efforts are already underway among COMESA and ECOWAS member states, although progress has been mixed on reforming domestic policy and regulation. The gains from trade are potentially significant, ranging from new market opportunities for seed producers to greater competition in seed markets that leads to lower prices and more rapid technological innovation. For VPCs, the success of harmonization will depend acutely on whether multiple seed categories are introduced, whether traceability systems are put into place, and whether the other recommended options discussed above are addressed.

Finally, these strategies all depend on continued public expenditure on breeding for host resistance to seed-borne pathogens and the production and distribution of early generation VPC seed. Ideally, these investments should be constant in VPC seed sector development.

None of the options presented here are immediate, short-term panaceas to the pervasive challenge of VPC seed sector development. They require long-term investments in programs and projects that put smallholders at the center of a change process, while challenging actor coalitions that have a stake in the status quo. But if the status quo is currently benefiting just a small share of the VPC seed system—as shown in our crop-country cases—there should be scope for considering better options.

5. Conclusion

Efforts to build effective quality assurance systems for VPC seed are challenged by the fundamental nature of VPC seeds and seed markets in many LMICs. Binding constraints include not only biological characteristics such as perishability, bulkiness, low multiplication rates, and high rates of pest and disease accumulation, but also economic characteristics: market frictions such as highly localized, dispersed, and fragmented market structures and the non-appropriability of gains from innovation in these markets. Few LMICs have invested sufficient public resources in designing regulatory systems that recognize these constraints and are tailored to the characteristics of each crop and the context in which farmers cultivate them. This is illustrated by the four crop-country combinations examined in this study.

Our findings demonstrate that the status quo in terms of seed production, distribution, and regulation is untenable: state-led production systems and programs combined with strict, centralized regulatory regimes necessarily limit seed market size and reach, thereby limiting smallholders' access to both new genetics and quality seed. This status quo neither provides credible oversight or direction to VPC seed systems nor addresses the needs or preferences of farmers, whether or not they are well articulated through market or non-market mechanisms. Solutions require longer-term strategies that rely not only on technological fixes such as advanced propagation systems and seed tracking apps, but also on a policy and regulatory environment that explicitly encourages the co-existence of multiple seed quality categories and the integration of multiple seed production and marketing systems.

We recommend a set of public policy, investment, and regulatory reforms that seek to recognize extant seed systems and end the marginalization or criminalization of informal seed production and trade; prioritize public investment into early generation seed production, distribution, and traceability systems; capacity development for rural entrepreneurs and farmer-based organizations in VPC seed production and marketing; introduction of multiple or alternate seed quality categories such as quality declared seed; decentralized quality assurance systems that combine internal systems with external oversight or the threat of such oversight; and better assessment and communication of risk associated with biotic and abiotic threats to VPCs that may be mitigated through the use of quality seed and improved genetics.

In fact, many of the elements in these policy and regulatory reforms are observed in the crop-country combinations covered by this study, or are common features of VPC seed systems in other countries with more mature seed markets. Yet in many LMICs, tension remains between specific actor coalitions with implicit interests in how seed systems evolve. In other words, there are winners and losers in policy change processes, and explicit recognition of the expected gains and losses to these groups is an essential part of the process.

CRediT authorship contribution statement

David J. Spielman: Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Marcel Gatto:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Tesfamicheal Wossen:** Writing – review & editing, Writing – original draft, Validation, Methodology, Investigation, Formal analysis, Conceptualization. **Margaret McEwan:** Writing – review & editing, Writing – original draft, Validation, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization. **Tahirou Abdoulaye:** Writing – review & editing, Supervision, Project administration, Investigation, Funding acquisition. **Mywish K. Maredia:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Guy Hareau:** Writing – review & editing, Supervision, Funding acquisition, Conceptualization.

Declaration of competing interest

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Data availability

The data used in this study are qualitative in nature and cannot be readily shared. However, key informant interview guides used in this study are available online (see IFPRI et al., 2019).

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