CGIAR POLICY INNOVATIONS

Rewarding the social benefits of small-scale farming

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A framework to inform policies and research to enhance smallholder contributions to public goods.

Rewarding the social benefits of small-scale farming[*]

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Abstract

Small-scale farmers are often encouraged to adopt innovations that generate significant social benefits, including improved nutrition, food safety, and environmental sustainability, yet market mechanisms frequently fail to reward these contributions. Adoption of such socially desirable practices remains below the social optimum due to unobservable attributes, high verification costs, limited production scale, and misaligned private incentives. We propose a simple framework that highlights four key dimensions influencing adoption: returns to farmers (R), adoption costs (C), inspection costs (I), and transaction scale (Q). Interventions can target these dimensions individually or in combination, such as reducing verification costs, aggregating production, subsidizing adoption, or enhancing market premiums. We illustrate this framework through three case studies: aflatoxin mitigation, biofortified crop adoption, and conservation agriculture, demonstrating how technology, policy, and market-based instruments can be coordinated to incentivize the adoption of socially beneficial innovations and practices. Our analysis emphasizes the importance of multidisciplinary approaches, integrated public and private actions, and dynamic interventions that account for both immediate and long-term social returns. By explicitly connecting adoption incentives with verification and market constraints, the framework guides research and policy toward more effective strategies to reward smallholders for their contributions to public goods and sustainable development.

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1 Introduction

Small-scale farmers are frequently trained or encouraged to adopt new inputs and practices, hereafter *innovations*, that generate private benefits for themselves—such as higher yields or increased resistance to pests and drought— as well as benefits to others. These *social benefits* may for instance relate to improved consumer nutrition, enhanced food safety, better processing quality, or environmental sustainability. In low-income countries, the value of these social benefits is rarely reflected in market prices, such that small-scale farmers' adoption of socially beneficial innovations tends to occur socially sub-optimal levels – even when other barriers to adoption are overcome [1, 2, 3, 4].

Why, then, are farmers in low-income countries not rewarded for the positive externalities they generate when adopting these innovations? A key constraint lies in the combination of unobservable socially-desirable attributes and limited scale: smallholder production and marketing typically occur at levels that make it difficult to signal or verify the presence of desirable qualities in the marketplace. This paper outlines these challenges using a simple conceptual framework that connects various strands of research along four key dimensions: the expected returns from adopting an innovation that generates socially desirable outcomes; the costs associated with its adoption; inspection costs (and the conditions under which they become relevant); and the scale of production (or the size of transaction) requiring inspection. We discuss how integrating insights across these dimensions could help improve our understanding of uptake constraints of innovations by smallholder farmers, and identify underexplored opportunities where targeted research could contribute to alleviate adoption barriers.

We illustrate this approach by examining innovations designed to encourage smallholders to contribute to socially desirable outcomes in the areas of food safety, nutrition, and environmental sustainability. For each, we examine innovations recognized as effective in generating social benefits while being accessible to small-scale farmers in Africa, but whose adoption remains limited compared to the social optimum. Using the proposed framework, we draw on past and ongoing research (and further discuss possibly new research areas) to discuss how small-scale farmers could be better encouraged in adopting these innovations in a way that produces the targeted social benefits.

Our goal in this exercise is fourfold. First, we argue that many aspects traditionally examined as informational problems within value chains—particularly those related to quality signaling for attributes that are costly to verify [5, 6]—should also be understood through the lens of public goods provision [7]. This re-framing highlights the essential role of public or socially-oriented financing to address this challenge whether that be through the development of technological solutions, investment in public goods or spending on subsidies of some form. Second, our framework indicates that there are multiple ways to increase the incentives farmers face and that cost-effective strategies will require multidisciplinary approaches. Third, we emphasize that the private returns to many current innovations are scale-dependent. As such, it is crucial to explicitly account for the incentives smallholder producers face when assessing the viability and potential uptake of these socially desirable innovations. Finally, we use this framework to explicitly identify where current market failures could be fixed and where non-market interventions will generally be required to incentivize smallholders' transition towards targeted innovations, at least in the short term.

2 A simple framework

Farmers produce goods with multiple attributes, some of which are directly observable, while others are not. Others in society interested in specific unobservable attributes may wish to compensate producers for their supply of these attributes. This could be consumers or a public agency interested in the unobserved quality of the good, or citizens interested in the environmental impact of how a good is produced (either local citizens interested in the impact on the local environment or global citizens interested in the impact on global emissions and resource use). However, when these attributes are *unobservable* – they cannot be verified through direct visual inspection of the product – incentivizing their provision becomes significantly more complex. From the producer's perspective, the decision to supply such attributes depends on the corresponding marginal production costs, which must be offset by an equivalent price premium or transfer. In some cases, the attribute is costless to provide because it is bundled with other characteristics highly valued by farmers. In these instances, farmers may supply the unobservable attribute regardless of compensation, though it may still be possible for the farmer to receive a price premium or a transfer reflecting the buyer's utility gain.

In other cases, supplying the unobservable attribute entails positive marginal costs, and without adequate compensation, farmers have no incentive to do so. The central challenge lies in verifying the presence of the attribute. When it is strongly correlated with other observable features of the product, producers can be rewarded through a premium aligned with the buyer's valuation. However, as inspection costs increase, for example through testing an attribute of the good or measuring and reporting on the environmental impact of production practices, the feasible level of compensation (buyer's valuation - inspection costs) declines, potentially to zero. As a general rule, any positive verification cost leads to an under-provision of the desired unobservable attribute [8].

This issue is particularly problematic in low-income countries agriculture, due to the typically small scale of production and transactions, combined with the largely fixed costs of testing for or verifying unobservable attributes in the goods supplied by farmers. Even when these fixed costs are modest, they can become disproportionately high with respect to the value associated with their supply.

Let I denote the fixed cost of obtaining reliable information on whether a farmer has adopted an innovation that generates a desired attribute, Q the quantity of product per transaction, such that the per-unit cost of revealing the presence of the attribute is $(I/Q) \geq 0$. Let R denote the per unit of product premium or transfer that the farmer receives for the supply of this attribute, and C the marginal cost of producing it by the farmer. The farmer adopts the innovation if the corresponding per-unit net return weakly exceeds a given reservation level of returns $\bar{\pi}$.[1] The per unit of product condition under which a farmer has an incentive to adopt such innovation is then:

$$(R - C) - (I/Q) \geq \bar{\pi} \tag{1}$$

This simple relationship highlights four broad categories of potential interventions. First, one may seek to lower the inspection cost per unit (I/Q) of product supplied by farmers.

- Reducing I: This can be pursued through technological and/or institutional solutions. Technological solutions include the development of testing methods enabling less costly measuring, reporting and verifying (MRV) of product attributes of production practices. Institutional strategies may involve public support to the testing or MRV infrastructure, or the coordination of its support by value chain actors in cases where they ultimately benefit from the increase supply of the desired attribute by small-scale farmers.
- Increasing Q: One approach is to enlarge the scale over which MRV is done by encouraging farmers to aggregate their products. It is however important to note that when Q is increased by aggregating across farmers it brings its own costs of information as farmers have to verify the unobserved characteristics of the goods and practices of others in the group. Thus, I can be lower for farmers based in the same locality, but these costs are rarely 0. For instance, public support to cooperatives in charge of commercializing smallholders' output are often promoted as a means to help farmers commercialize higher quality products. However, such arrangements often underperform or become limited to lower-quality products due to coordination failures and free-riding among cooperative members[9, 10, 11]. Alternatively, farmers can be brought together earlier in the production cycle and encouraged to produce and market together (e.g., cluster/block farming in Ethiopia, Ghana, Malawi, Tanzania, and Zambia). However, sustaining these schemes is often difficult, as individual incentives for effort may not be aligned, leading to short-lived successes.

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[1] The reservation level may vary across farmers, reflecting heterogeneity in attitudinal factors (e.g. risk aversion), knowledge constraints (e.g. education), and other individual-level characteristics that have been shown to influence the adoption of agricultural innovations among smallholder farmers in low-income countries.[1]

Even if the per-unit inspection cost is lowered, one must ensure that by investing in the provision of socially desirable attributes of their products, farmers obtain private rewards that exceed the associated cost: $(R - C)$.

- Increasing R: Rewards to farmers can be enhanced in several ways. One is by increasing the market premium for goods that can credibly be linked to socially desirable outcomes. Another is through direct payments to farmers who adopt socially beneficial innovations. An example of this would be payments from voluntary carbon markets or public payments for ecosystem services where farmers are compensated on the basis of land or water management practices.
- Lowering C: Subsidies can be targeted at lowering the adoption costs of the innovation, to the point where the corresponding private benefits approximate social gains. For example, non-linear subsidies for the use of an aflatoxin bio-control product (Aflasafe) have been designed to more precisely target portions of a farmer's land dedicated to local market sales [12].

Figure 1 presents the proposed framework as a two-dimensional graph. The vertical axis represents the per-unit cost of inspection, while the horizontal axis captures the gap between the private return of a farmer adopting a socially-desirable innovation and its associated costs.[2]

Each innovation can be conceptualized as a specific point within this space, defined by the prevailing values of I, Q, R and C at a given time and in a particular location. The $(I/Q) = (R - C)$ line delineates combinations of these values where information costs offset net social returns. Only technologies or practices that lie below this line (indicating information costs are not prohibitively high) and to the right of the vertical line at $R - C = 0$ (where rewards to social returns exceed private costs) fall within the feasible adoption region (area IV).

The infeasible region can be further disaggregated. Technologies or practices falling within area III are characterized by negative net returns to the farmer, irrespective of information costs. In such cases, the priority is to either enhance the farmers' rewards for the social returns (R) or reduce the marginal cost of adoption (C). For technologies located in area I, adoption would require increased rewards, but may also benefit from reduced information costs. Those situated within area II may be made adoptable by lowering either information costs or increasing rewards, or both. This framework thus clarifies the intervention levers needed to expand the set of viable technologies for smallholder engagement.

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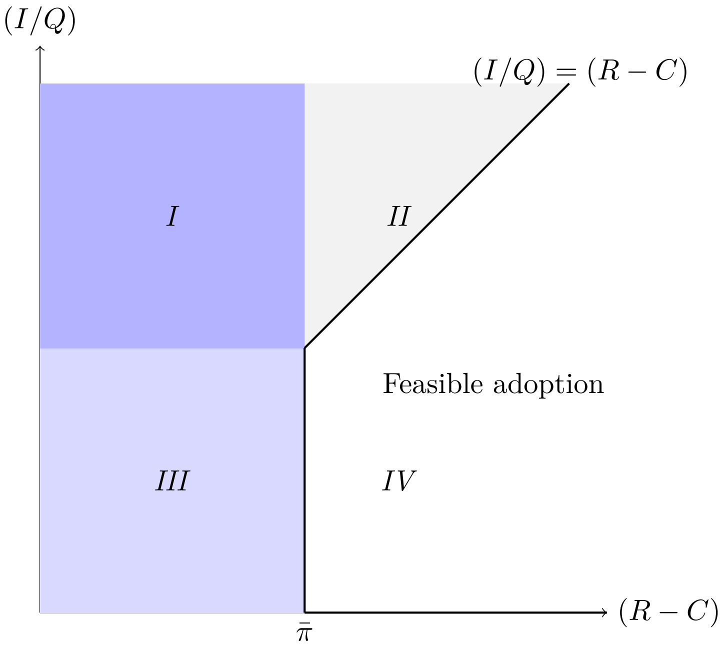
[2] As is standard in economics, we refer to the costs of providing the desired attribute as the increase in production costs compared to the farmer's best alternative technology or practice.

Figure 1: Conceptual framework



We note that for initial locations in areas I and II, the shortest path to feasible adoption (area IV) will involve a combined reduction in (I/Q) and increase in $(R - C)$, hinting at the importance of multidisciplinary approaches to addressing adoption incentive constraints. Accordingly, addressing only one element of the equation - whether I, Q, R, or C - will yield limited results unless large reduction in I or C, or markedly increase in Q or R can be obtained. Alternatively, even modest reductions in I or C may be effective when accompanied by concurrent increases in R or Q.

Table 1 outlines illustrative interventions that can reduce cost of inspection I, increase transaction quantities Q, enhance returns R, or lower adoption costs C. Efforts to reduce the cost of inspection (I) include the development of technologies that reduce testing costs, the provision of subsidies to offset inspection expenses, and the strengthening of MRV systems. Such interventions, however, require substantial research capacity as well as institutional mechanisms for the establishment and enforcement of credible standards. Enhancing transaction size (Q) through collective action and specialization – such as the organization of farmer groups or the promotion of cluster and block farming – can reduce inspection costs per unit. The success of these measures depends on effective coordination among producers, alignment of incentives, and robust risk management systems. Interventions designed to enhance producer returns (R) include public awareness campaigns that stimulate consumer demand for products embodying socially desirable attributes or practices, conditional payment schemes that incentivize adoption, consumer subsidies, and the implementation of regulatory instruments. These approaches rely on mechanisms for monitoring quality and adoption, adequate public financing, and strong institutional capacity for oversight and enforcement. Similarly, interventions intended to lower adoption costs (C), such as agricultural R&D, extension services, and producer subsidies, necessitate advanced research infrastructure, efficient extension systems, and publicly funded subsidy mechanisms.

Table 1: Examples of interventions to alter IQRC

Intervention	**Aim**	**Requirements**
Reducing I		
Testing R&D	Develop means to reduce the cost of testing	Global or national capacity in research.
Testing subsidies	Subsidizing the cost of the test	Test is specific to identifying the characteristic.
Support certification	Support the testing and certification infrastructure (or coordination by value chain actors)	Strong public institutions for defining and enforcing grades and standards.
Increasing Q		
Promote farmers groups	Increase the size of transaction through collective commercialization	Group capacity to monitor and enforce farmers' adoption of innovation.
Promote block farming	Increase the size of transaction through collective production	Strong coordination and alignment of individual incentives between farmers.
Promote specialization	Increase the size of transaction by reducing farmers' crop diversification	Well-functioning means to lower production and market risks at farmer-level.
Increasing R		
Public awareness campaign to consumers	Increase consumer demand for targeted attribute of good	A way for the unobserved quality to be observed.
Conditional payments to producers	Reward producers' adoption of innovation	A way for the adoption to be observed.
Consumer subsidies	Subsidize the purchase of goods with the required characteristic	A way for the unobserved quality to be observed.
Regulation on consumer markets	Decrease market return of non-adopting the innovation	Strong public institutions to design and enforce regulations.
Reducing C		
Agricultural R&D	Develop innovations with lower costs of adopting by small-scale farmers	Global or national capacity in research.
Extension	Provide farmers with information on innovation and cost-effective adoption	Broad reaching and reliable extension services (physical and/or digital).
Producer subsidies	Lower financial cost of adoption	Subsidy schemes targeting social-returns of innovations.

While extensive research exists on each individual parameter, there is a pressing need to move toward a research agenda that explicitly considers their interactions. Below, we illustrate this approach by outlining real-world examples where integrating existing strands of research may generate synergies and yield effects greater than the sum of their parts.

3 Three illustrative case studies

3.1 Food safety – Promoting Aflatoxin-free production

The issue: Foodborne disease-related deaths are estimated to be the highest per capita in Africa, causing 137,000 deaths and 91 million illnesses annually, underscoring the close link between agricultural systems and public health [13]. Visually undetectable food safety problems that contribute to this situation are widespread in the region. Reported examples include Salmonella and other pathogens in foods at prevalences up to 44% in Burkina Faso [14], high coliform counts in Kenya's informal milk chains [15], pesticide residues exceeding safety limits in tomatoes and vegetables in Burkina Faso and Uganda [16, 17], antibiotic residues in animal products [18], and heavy metals and pathogens in wastewater-irrigated vegetables in Accra [19].

Aflatoxin contamination is among the most serious food safety threats globally, resulting in significant health developmental, trade and economic problems in the affected regions[20] and notably in sub-Saharan Africa[21]. Given climate conditions and dependence on susceptible staple crops like maize and groundnuts, studies across sub-Saharan Africa report persistently high levels of human and animal exposure [22, 23, 24, 25]. Acute exposure can be fatal [26, 27], while chronic exposure is linked to child stunting, cancer, and weakened immunity [28, 29, 30, 31, 32].

Aflatoxin-producing fungi infect crops before, during, and after harvest and can produce aflatoxins during all these stages if conducive conditions for toxin formation occur[33, 34]. Several practices can reduce crop aflatoxin content at different stages of the crop value chain[35, 34, 36, 37, 38] but, when used in isolation, aflatoxin contamination often occurs above safe and permissible levels, particularly in tropical and subtropical regions[39]. Another approach is biological control, notably *Aflasafe*, which targets Aspergillus flavus, the fungus responsible for aflatoxin production. Despite its growing availability across the region since its introduction in 2014 and its efficacy in reducing aflatoxin levels in maize and groundnut across diverse farming systems, notably in Nigeria [40], uptake of Aflasafe among smallholders remains limited in Africa.

Reducing I/Q: Aflatoxins are imperceptible outside of dedicated tests: contaminated crops are visually, olfactorily, and gustatorily indistinguishable from uncontaminated ones. Currently available testing for the presence of Aflatoxins is sample-based and largely invariant with the size of the consignment that is tested: the cost is the same whether one tests for a 50kg or a 5MT consignment. Public and private R&D efforts have recently focused on developing detection methods better suited to smallholder value chains in low-income settings, particularly for crops like maize and groundnuts. For effective integration into these systems, tests must balance accuracy, usability, and affordability. One such example is ICRISAT's portable competitive ELISA (cELISA) kit available since 2016, designed to function without specialized laboratory personnel, offering reliable (+/- 10ppb) results in under 15 minutes at a cost of less than 2 USD per test. More recently (since 2022), ICRISAT, in collaboration with PureScan, introduced an AI-based diagnostic tool priced around 50 USD, capable of delivering rapid and precise (+/- 1ppb) results within seconds at low marginal costs as it does not require any consumable. If made available (possibly at subsidized rates) to farmers, cooperatives or rural traders, these equipments can be used to assess aflatoxin contamination rate at farmers' level (or their use of Aflasafe) and signal it so that they are rewarded for it. Public support to the existence of reliable testing and certification could help ensure that small-scale farmers are indeed rewarded for their efforts and investments towards the supply of aflatoxin-free food products.[41].

Lowering per-unit inspection costs through product aggregation is another common strategy in quality assurance programs. In Nigeria, the AgResults program promotes Aflasafe adoption by aggregating farmers' outputs for collective testing by corporate buyers [42], a model also seen in Senegal's groundnut export cooperatives [43]. But these arrangements, which impose strict quality oversight, typically serve export markets, leaving local consumer markets exposed to high aflatoxin risks. Outside such contracts, aggregation has shown limited effectiveness in promoting non-visible quality traits for domestic value chains.[3] A yet-untested alternative is to introduce more flexibility in the level of Q, by allowing farmers to choose the scale at which testing occurs instead of systematically promoting it at the full group level where observability and trust of *all* others' engagement with the innovation is oftentimes limited. Even simple coordination between two farmers could halve testing costs, offering a more flexible and potentially scalable approach than relying solely on fixed cooperative or cluster/block farming structures.

Increasing R–C: Enhancing farmers' returns from Aflasafe use often relies on market-based mechanisms that leverage consumer willingness to pay for safer food. Evidence on consumers' willingness to pay suggests limited but positive demand [45, 46], which tends to increase following targeted information campaigns [47, 48].[4] Even when consumer demand is established, one must ensure that the food safety premium paid by the final consumer is

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[3] In Ethiopia, farmers whose products were tested and rated as of higher quality regarding flour extraction rate sold less through cooperatives than untested peers with similar levels of quality [44].

[4] Oftentimes however, the demand for certified and safer products skews toward more affluent consumers, raising equity concerns, especially if poorer populations are left with the more contaminated products [46, 49].

passed through suppliers at each stage in the market chain all the way to producers. This may require coordination of a sometimes large number of actors [50]. As few policies directly subsidize food for its health attributes, an alternative is the enforcement of food safety standards, as practiced in the EU and US, which shifts the burden of safety from individual choice to regulation, though it requires accounting for enforcement costs. Importantly, the enforcement of food-safety standards would likely increase overall food prices by the added cost of Aflasafe treatment per unit of product, effectively internalizing the health benefit in the price faced by all consumers.

Regarding the cost of adoption (C), proper application of Aflasafe typically requires 10 kg per hectare. While labor requirements are minimal, the product cost—approximately USD 20 per hectare—is significant for many small-scale farmers. Even with partial subsidies, adoption may remain suboptimal. Absent market reward, evidence suggests that farmers who are aware of aflatoxin risks tend to selectively protect the portion of their harvest intended for household consumption [49]. There is a role for public research and development on reducing the cost of Aflasafe production. If this is not possible, public funds could subsidize Aflasafe to smallholder farmers, thereby safeguarding public health. Where full subsidies are deemed too costly, geographically targeted approaches could be considered. On-going research is seeking to leverage time and geolocalized data on aflatoxin contamination to calibrate AI models able to predict areas most susceptible to aflatoxin contamination given weather patterns ahead of the agricultural season [51]. This information could be used to target the subsidies to producers in those locations. Another approach is to design subsidy schemes that specifically targets the portion of farms which produce food for the market [12].

Key takeaways: The pre-intervention location of the aflatoxin problem can be mapped to area II of Figure 1 where the most direct route to feasible adoption will likely involve both reductions in (I/Q) *and* increases in ($R - C$), signaling intervention synergies. In the absence of affordable and widely accessible diagnostic tools, the most effective approach may involve combining health information campaigns with fully subsidized (and possibly targeted) distribution. However, recent advances in aflatoxin detection technologies may open pathways for market-based solutions, provided there is sufficient demand. If demand proves robust (potentially in response to other investments in public information campaigns), Aflasafe could be promoted at cost. Otherwise, adoption will likely continue to rely on some level of public subsidy to internalize its health-related social benefits.

3.2 Nutrition – Encouraging the adoption of biofortified crop varieties

The issue – While global trends in micronutrient deficiencies have generally declined between 1990 to 2019, sub-Saharan Africa continues to bear a significant burden, particularly for iodine, vitamin A, folate, zinc and iron deficiencies. These deficiencies are driven by factors such as inadequate dietary diversity, poor sanitation, frequent infections, and limited coverage of supplementation programs. The health consequences are severe, including adverse pregnancy outcomes, congenital malformations, impaired cognitive development, increased perinatal, infant and child mortality, and reduced resistance to infections, diarrheal diseases, measles and other illnesses [52].

Supplementation, food fortification, and biofortified crop varieties are three strategies that can address deficiencies when nutrition requirements cannot be met through dietary intake alone. Biofortification (increasing the concentration of particular micronutrients in staple crops through agronomic, transgenic techniques, and plant-breeding approaches) has proven to be a feasible and cost effective means of delivering micronutrients [53, 54, 55]. Yet, while more than 284 biofortified (rich in iron, vitamin A, or zinc) varieties of 12 crops have been released in 22 African countries over the past two decades, smallholders' adoption of these varieties remains suboptimal [56, 3, 57, 58].

Reducing I/Q: Some biofortification interventions result in visible changes—such as the orange or yellow colors of Vitamin A-enriched sweet potatoes , cassava and maize. In contrast, other biofortified traits are not visually detectable and require specialized testing to assess nutrient levels. As for Aflatoxins, such assessments are typically sample-based and independent of the size of the product batch to be evaluated. Several analytical technologies are currently available to accurately measure the concentration of micronutrients in biofortified crops, including minerals (e.g., via X-ray fluorescence [XRF] spectroscopy), vitamins (e.g., using high-performance liquid chromatography [HPLC]), and other beneficial compounds. However, these methods are often costly and largely inaccessible in rural areas where many smallholder farmers operate. Support to emerging technologies offer promising, lower-cost alternatives capable of providing rapid assessments at the farm level or at local aggregation and collection centers. For example, portable near-infrared spectroscopy that uses light to analyze the chemical composition of materials could yield rapid, non-destructive, and cost-effective analysis of nutritional content of biofortified grains [59, 60, 61]. The advancement in sensor technology, such as integrating smartphone-based detection methods and paper-based sensors can also facilitate real-time and on-site analysis of both nutritional components in grains [62]. Lastly, remote sensing approaches leveraging hyperspectral sensors and advanced modeling, also show a strong promise for non-destructive and scalable assessment of crop nutrient quality across space and time [63].

Aggregation at production (e.g., through cluster/block farming) and marketing stages (e.g., producer groups) prior to verification would be one way to lower the per-unit costs for producers (raising Q). However, as with Aflatoxin, challenges include intentional or unintentional mixing of quality (free-riding or coordination failures in production) prior to verification, which cannot be traced and are hard to correct for.

Increasing R–C: Improving farmers' returns from producing biofortified crop varieties generally relies on certification schemes that leverage consumers' willingness to pay for nutrient dense food. While the evidence suggests differences across contextual factors and visibility of nutrient traits, consumers in low-income countries generally show a positive willingness to pay a premium for biofortified crops that increases with the provision of nutritional information and the visibility of the trait [64, 65, 66, 67, 68, 69].

Fixing markets for biofortified crops may however require public policy support, as some studies show a negative willingness to pay for biofortified crops with visible traits, apparently linked with neophobia around unfamiliar food appearances [67, 70, 71]. Public policy support may require a financial commitment to increase demand. This could be quite low cost such as funding marketing campaigns to reduce consumer concerns and increase consumer demand, or could be more substantial, such as providing time-bound subsidies to biofortified crops to increase use and familiarity with new food products. This spending can be justified by the large and lasting economic, social, and medical impacts of (micronutrient) malnutrition. Even where consumer demand for biofortified crops is positive, enhancing farmers' reward to their supply of it may require coordination of key value chain actors to ensure/facilitate the pass-through of premiums from consumers to farmers, via intermediary actors. Alternatively, non-market approaches may leverage recent advances in remote sensing technologies to provide geographically targeted subsidies to farmers who produced nutrient dense crops [63].

Expected yield is often one of the most critical factors influencing farmers' production decisions. Although biofortified crop varieties typically entail production costs comparable to those of conventional varieties, their expected yields must be at least equivalent to conventional crops to support widespread adoption [72, 47, 73]. To enhance adoption, micronutrient traits should be integrated into advanced lines of widely adopted, agronomically superior (mega) varieties and, when they exist, farmers should be informed about the absence of tradeoffs between nutrition content and other desired varietal attributes [74]. In addition to agronomic and economic considerations, sensory and sociocultural attributes of biofortified crops can impose indirect costs on farmers, particularly since they often consume a portion of their own production. Although biofortified varieties are generally well accepted from these perspectives, future breeding efforts can further support large-scale adoption by aligning with localized preferences related to crop color, preferred food products, cooking ease, storage characteristics, and other culturally relevant traits (e.g., [58]).

Key takeaways: Non-visible versions of the biofortification problem can be mapped to area II of Figure 1, where the most direct route to feasible adoption will likely involve both reductions in (I/Q) *and* increases in $(R - C)$. The situation may however be different for visible versions of the problem (e.g., orange-fleshed sweet potato, orange maize) for which the low verification costs sometimes comes with negative consumer willingness to pay (e.g., orange maize), which places the pretreatment situation in area III of Figure 1. There, adoption can only be promoted through increases in R, through direct public subsidies or targeted information on nutrition and health benefits through individual or collective behavioral change campaigns aimed at increasing consumer demand.

3.3 Environment – Promoting adoption of conservation agriculture

The issue: Agriculture in low-income countries, particularly in sub-Saharan Africa, is a significant source of greenhouse gas (GHG) emissions, stemming from both direct farm activities and land-use changes. Key contributors include methane from livestock enteric fermentation and irrigated rice production, nitrous oxide from inefficient fertilizer use and poor manure management, and emissions from widespread residue burning [75]. Indirect emissions result from land conversion—especially deforestation and grassland clearance for cropping—which depletes soil organic carbon (SOC) and above-ground biomass. These impacts are worsened by soil-degrading practices such as intensive tillage, residue removal, and inadequate nutrient cycling, accelerating carbon loss and limiting long-term carbon sequestration potential [76].

In response, the 2015 COP21 summit in Paris introduced the voluntary '4 per 1000 Initiative: Soils for Food Security and Climate', promoting regenerative farming practices to enhance soil health and climate resilience. One recommended practice is conservation agriculture (CA), which combines crop diversification (e.g., cereal-legume rotations), permanent soil cover (e.g., crop residues or cover crops), and minimal soil disturbance (e.g., no or minimum tillage). While CA's effectiveness has been debated, recent studies (e.g., [77]) indicate it can increase SOC, particularly in dry regions like Africa, where yield effects are neutral or positive. Despite this, adoption by small-scale farmers remains low, covering only about 1.25% of cultivated land [78].[5]

Increasing net soil carbon storage offers a promising strategy for climate mitigation and sustainable food production by limiting CO2 emissions, capturing atmospheric CO2 and enhancing soil quality. However, incentivizing smallholders to adopt conservation agriculture through compensation for its positive environmental externalities is challenging, given the difficulties in monitoring adoption, tracking changes over time, and verifying the integrated application of its three key practices, which are thought to deliver the most significant environmental gains.

Increasing R–C: Conservation Agriculture remains sparsely adopted in sub-Saharan Africa, largely due to the absence of strong economic incentives for smallholder farmers [81].

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[5] An important literature questions claims about about adoption rates of CA, noting that very different numbers are obtained whether one considers as "adopter" those who implements at least one of the key recommended practices (e.g. no-till) or the full set of recommended practices [e.g. 79, 80].

A central challenge—especially for resource-constrained farmers—is that many of the private benefits (e.g., yield improvements) tend to materialize only after several years, whereas some of the associated costs are incurred immediately. These costs (C) include potential short-term yield reductions, increased weed pressure requiring additional labor or chemical control, loss of crop residues for livestock feed, and limited access to appropriate equipment for direct seeding [82, 78].[6]In the absence of immediate profitability, the non-adoption of CA by African smallholders may constitute a rational economic choice and further lead to high rates of dis-adoption [83]. Several complementary interventions could also help lower the cost of adoption by easing access to labor-saving technologies such as mechanized planters or chemical weed management. An additional cost is the cost of learning how to implement CA practices correctly. A related study in Niger highlights the importance of training and public awareness campaigns in encouraging take-up of soil conservation practices [84].

In areas experiencing increasing seasonal variability in production conditions — particularly irregular rainfall — the incentives to adopt CA may increase naturally, as its practices improve water retention and reduce runoff, potentially delivering more benefits (R) in the short term as compared to conventional approaches. When these short-term private benefits remain insufficient to sustain farmer adoption of CA, additional incentives may be necessary to compensate for the positive environmental benefits generated. Such instruments may mirror performance-based environmental programs, including payments for forest conservation in Uganda [85] and efforts to curb crop residue burning in India [86]. Publicly funded payments can be justified by the environmental benefits of CA, both those that are short-term such as improved surface soil protection through residue retention and long-run benefits such as increased SOC, soil moisture retention and water-use efficiency, and greenhouse gas (GHG) mitigation. Some of these benefits accrue to the individual farmer, but they also have public good characteristics — particularly under increasing climate stress [87]. Market-financed payments utilizing carbon offsetting finance can be explored to support farmers, in a way that helps reconcile the short term costs born by farmers engaging in CA, and the longer term social benefits associated with it.

Reducing I/Q: Whether farmers adopt Conservation Agriculture (CA) must be inferred from observing practices at the field level. Monitoring individual farmers, however, involves fixed costs that can become prohibitively high in smallholder settings. This challenge has long been noted in the micro-insurance literature, where recent advances in weather-index insurance have partially addressed similar constraints. In the context of CA, emerging remote sensing technologies offer promising solutions for monitoring adoption (I) and providing the basis for MRV. For example, [88] demonstrate in Belgium that combining time series from optical satellite imagery (Sentinel-2, Landsat-7 and 8), and radar data (Sentinel-1) can distinguish conservation from conventional farming with 92% accuracy. Such methods could

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[6] These may be compensated by reduced costs related to land preparation.

be adapted for smallholder systems in Africa, although several operational challenges remain (e.g., limited land registration systems, dynamic functional field boundaries in smallholder systems, lower scope for remote detection in inter-cropped systems). Such approaches must however be complemented by precise measures of the social benefits generated from farmers' adoption of CA. Evidence shows that the magnitude of SOC gains from CA, as well as their dynamics through time – whether steadily rising, plateauing, or peaking then declining -— depend strongly on climate, soil type, and residue management. While a 17-year trial in Spain find that SOC gains under no-till practices peaked after eight years before gradually declining,[89] evidence shows sustained SOC accrual in semi-arid Morocco,[90, 91] humid regions of Brazil,[92] and cool climates of the Canadian Prairies,[93]. These contextualized patterns highlight the importance of spatially disaggregated evidence in order to guide policy and design incentive mechanisms favoring farmers' engagements with CA.[94]

In addition to these technology-driven reductions in the cost of I, market-based systems could also rely on paying groups of farmers rather than individual farmers, effectively increasing the size of the operational units to be verified (Q). This could be through groups of farmers undertaking the same practices through cluster/block farming and similar schemes. Recent experiences with cluster/block farming in Ethiopia, Ghana, Malawi, Tanzania, and Zambia suggest that this may be viable, albeit with strong state support [e.g., 95].

Key takeaways: Conservation Agriculture can be mapped to area II of Figure 1, where the most direct route to feasible adoption will likely involve both reductions in (I/Q) *and* increases in $(R - C)$. A further challenge with CA stems from the predominantly long-term nature of its private and social benefits. The broader issue of reconciling short-term costs with long-term benefits is common to many economic decisions but is particularly acute for smallholders, who often lack access to suitable financial instruments. Technological advances that reduce the cost of verifying compliance with CA practices, combined with payments for ecosystem services (whether publicly financed or market-based), could help facilitate a sustained transition. The visibility of adoption plays a critical role in enabling incentive structures that reward observable compliance (i.e., affecting returns R). As adoption becomes more widespread and the system approaches a new equilibrium where $R - C \geq 0$, the marginal cost of monitoring (I) may approach zero.

4 Towards an integrated research-policy agenda

This paper presents a framework for promoting small-farmers' adoption of innovations associated with important social benefits, illustrated through three case studies. While many conventional agricultural innovations have negligible inspection costs, generate primarily private returns, and thus fall outside the framework's main focus, most contemporary public R&D targets *sustainable intensification.* These innovations deliver public benefits—environmental services, food safety, improved nutrition—that are often excluded from R, meaning that focusing solely on reducing C risks leaving significant social gains unrealized.

From this framework, we identify three priorities for improving public R&D systems.

First, integrated, cross-disciplinary research is needed to measure and enhance the public-good value of smallholder innovations. Examples include quantifying health gains from reduced aflatoxin contamination, nutritional benefits from biofortified crops, and carbon emission and sequestration from Conservation Agriculture (CA). In many cases, estimation remains contested, underscoring the need for robust metrics. Equally important is advancing tools to cost-effectively verify quality attributes or production practices not visible in final products, such as remote sensing for CA, portable near-infrared devices for grain quality, and improved diagnostics for aflatoxin detection.

Second, the framework clarifies when market failures for unobservable quality attributes can be addressed through institutional or technical innovations and when non-market instruments are preferable. Market-based approaches work when inspection costs fall to feasible levels, but public action is often required to coordinate value chain actors and manage distributional effects. Where fixing markets for unobservable quality remains prohibitively costly, policies should instead focus on increasing $(R-C)$, through adapted subsidy schedules, conditional payments or regulations.

Third, the opportunity space—I, Q, C, and R—is dynamic and can shift with early interventions. Many sustainable intensification practices, including CA, yield modest initial returns but increase over time, making early-stage investments akin to public goods. Similar dynamics occur on the consumer side: when private utility diverges from public utility (e.g., nutritional or food safety benefits), public investment in R, coupled with education, can shift demand until markets sustain the desired equilibrium. In this way, short-term non-market incentives act as transitional "nudges" toward self-sustaining outcomes.

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