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RESEARCH ARTICLE

Inclusive innovation in crop gene editing for smallholder farmers: Status and approaches

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Gene editing technologies like CRISPR/Cas are breathing new life into expectations about the benefits of genetically modified crops for smallholder farmers in the global South. In this article, we put these expectations to the test. We have interrogated both whether crop gene editing is employed for smallholder farmers and how this is done in ways that are more or less inclusive. To this end, we systematically investigated projects using gene editing for smallholder farmers and analyzed their activities using the framework of inclusive innovation. We have 3 main findings. First, gene editing indeed can be used to target crops and traits that may benefit smallholder farmers. We found 30 projects that target a variety of crops and traits for smallholders. Second, the use of gene editing for smallholder farmers is emerging slowly at best. The number of projects is relatively small, the set of crops that is targeted is relatively limited, and the number of countries that engage in these activities is small. And third, we found 2 distinct approaches to inclusive innovation that we describe as spacecraft approach and helicopter approach to inclusive innovation. We argue that the inclusive innovation framework should not be used as a checkbox—where inclusion is achieved if all types of inclusion are covered—but instead should be used as a tool for rendering visible the choices that have been made in inclusion, thus opening up such choices for critical scrutiny.

Keywords: Gene editing, Smallholder farmers, CRISPR, Inclusive innovation, Distributive justice

1. Introduction

Recent advances in gene editing technologies are said to offer unique opportunities to improve food security among smallholder farmers in the global South (Gates, 2018; Ma et al., 2018). Gene editing technologies like CRISPR/Cas9, ZFN, and TALEN are promised to alter genetic material in living organisms with great precision and can, for example, be used to create drought-resistant crops or more nutritious crops.[1]

These expectations are fueled by the supposed accessibility of gene editing technologies. Compared to older generations of biotechnology, gene editing (or genome editing) technologies are claimed to be relatively cheap and easy to use and may, thus, more readily be used by research institutes and companies with fewer resources, including those in the global South. This lowers the barriers by using biotechnology for the improvement of crops that are commercially less interesting, like orphan crops that are predominantly grown by smallholder farmers in the global South. Indeed, recent review papers show gene editing technologies have already been applied to a variety of tropical crops like rice and yam and to orphan crops like cassava and sorghum (Haque et al., 2018; Venezia and Krainer, 2021).

At the same time, there are reasons to be skeptical about these claims. In the past, similar promises have been made for genetically modified (GM) crops, and much of those promises remain unrealized (Jansen and Gupta, 2009). GM crops have not been widely adopted by smallholder farmers in the global South (Fischer et al., 2015) and in several regions that were initially regarded as success stories for smallholder adoption of GM crops—like Burkina Faso and the Makhathini flats in South Africa—the use of GM crops has since been renounced (Gouse et al., 2008; Dowd-Uribe and Schnurr, 2016; Beumer and Swart, 2021). Various scholars have demonstrated that corporate control over crop technologies like GM has directed developments in crop improvement away from smallholder farmers (Fischer, 2016) and that even when GM was actively portrayed as "pro-poor," this failed to influence their design, as few activities were undertaken to develop crops that were specifically designed to address the needs of smallholder farmers (Glover, 2010a). A recent overview succinctly concluded that GM crops do not

1. Clustered regularly interspaced short palindromic repeats (CRISPR), zinc finger nucleases (ZFN), and transcription activator-like effector nucleases (TALEN) are different techniques for gene editing.

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"sufficiently take into consideration smallholder farmers' lived realities in the form of their geographic, social, ecological, and economic contexts" (Schnurr, 2019, p. 6).

There is, hence, significant uncertainty over the potential of crop gene editing for smallholder farmers, and there are hardly any empirical studies that have put this to the test. There has been ample research on various other societal implications of gene editing—ranging from health risks to democratic governance and from ethical concerns to ownership (e.g., Nuffield Council on Bioethics, 2016, and various articles in this issue). Yet, the potential implications for the global South have not yet been part of that discussion. Moreover, little is known about *how* gene editing technologies are employed in the projects that do explicitly seek to benefit smallholder farmers in the global South. What crops and traits are currently targeted in such projects? To what extent are different smallholders farmers included? How are the resulting crop varieties envisioned to reach different smallholder farmers? These questions are especially pertinent in the light of Montenegro de Wit's (2020) recent finding that despite promises that CRISPR will democratize agricultural biotechnology, in reality, there is little room for democratic participation of different actors.

In this article, we aim to make two contributions to this debate. Our first contribution is to empirically test claims by the likes of Bill Gates (2018) that gene editing is already "accelerating research that could enable (. . .) farmers in the developing world to grow crops (. . .) that are more productive, more nutritious, and hardier." To this end, we will study whether gene editing is specifically used to improve food security among smallholder farmers in the global South. This contribution is informed by literature in the sociology of expectations that calls for critically assessing the promissory narratives on emerging technologies (Nordmann and Rip, 2009; Lucivero et al., 2011).

Our second contribution is to study how *inclusive* the use of gene editing for smallholder farmers currently is. We start from the position that we cannot take for granted that gene editing researchers know to what ends gene editing can best be used to benefit different smallholder farmers. It is notoriously difficult to identify smallholders' demand for seed (Stone and Flachs, 2014; Almekinders et al., 2019), and improved varieties often fail to reach smallholder farmers despite the best of intentions (Spielman and Smale, 2017). In this context, various schools of thought have emphasized the importance of involving stakeholders at an early stage of technological development (Bijker, 2010; Owen et al., 2012), and farmers specifically (Almekinders et al., 2019; Beumer, 2021). We build on this literature. By focusing on inclusion, we aim to explore whether smallholder farmers are currently included in attempts to use gene editing for their benefit, who exactly is included, and how this is done.

We will examine whether and how gene editing is used for the benefit of smallholder farmers by focusing on research *projects*. We have mapped the activities of gene editing projects worldwide and conducted 23 interviews with researchers involved in projects that specifically target smallholder farmers. Projects are a suitable unit of analysis for mapping research activities at an early stage of technological development when ongoing research activities are not yet published and improved crops have not yet arrived in the field, as is the case for crop gene editing. Moreover, as this specific form of organizing research activities, projects offer more opportunities for actively including smallholder farmers compared to what may be achieved by individual researchers. As such, projects offer a suitable unit of analysis for understanding inclusive innovation in gene editing.

We will systematically identify projects that use gene editing for smallholder farmers, and we will assess how inclusive these projects are by drawing on the ladder of inclusive innovation (Heeks et al., 2014). This framework distinguishes 6 levels at which inclusion can occur, as is further explained in the next section. For example, an innovation at Step 1 is inclusive in terms of intent, such as a product designed to meet the needs of the poor; an innovation at Step 3 actually has a positive impact on the poor; and at Step 5, innovations make socioeconomic, institutional, or organizational structures of production more inclusive. This framework thereby offers a broad perspective on the various ways in which inclusion can occur. As we will show below, we found 2 distinct approaches to inclusive innovation in the limited number of projects that explicitly seek to use gene editing for smallholder farmers.

2. Inclusive innovation

Inclusion has long been a prominent topic in fields like development studies, Science and Technology Studies (STS), and Responsible Research and Innovation (RRI). Scholars across these fields have argued for the importance of including stakeholders and publics to ensure that the process and production of innovations become responsive to societal needs (Owen et al., 2012). This is important for gene editing because the purposes for which it will be put to use are not set in stone, and the impacts of enhanced crops can be highly diverse and extend into domains that have little to do with the impact that was initially intended (Beumer, 2019; Macnaghten et al., 2022).

Key to this understanding of inclusion is the timely identification and incorporation of needs and concerns of diverse societal groups (Owen et al., 2012; Stilgoe et al., 2013). To this end, scholars working on RRI and STS have developed various new governance arrangements for inclusion, such as citizen juries, consensus conferences, and hybrid forums, and various other forms for assembling "mini-publics" (Rowe and Frewer, 2005; Goodin and Dryzek, 2006). These forms are often rooted in concepts of direct and deliberative democracy (Nahuis and Van Lente, 2008) and promote responsible innovation by complementing existing governance arrangements with institutional forms for the *direct involvement* of various societal groups.

These arrangements capture only a small subset of measures that can be taken to ensure inclusion, however. In this context, inclusive innovation provides a valuable alternative framework that helps understanding inclusion and exclusion in ways that move beyond direct participation. This literature emerged from the concern that

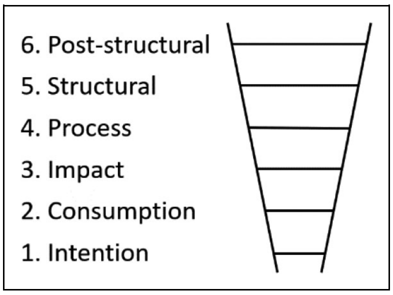

Figure 1. Ladder of inclusive innovation.

innovation is disproportionally targeted at wealthy consumers, and literature on inclusive innovation offered concepts for redirecting such "conventional" innovation activities toward developing innovation that also benefit marginalized communities (Heeks et al., 2013; Mortazavi et al., 2021). Literature on inclusive innovation predominantly focuses on corporations, governments, and other players from conventional "innovation systems," often situated in the global North (Foster and Heeks, 2013; Chataway et al., 2014; Planes-Satorra and Paunov, 2017), though increasingly the concept has been applied to grassroots innovation movements in the global South (Fressoli et al., 2014; Patnaik and Bhowmick, 2020).

The literature on inclusive innovation has drawn attention to a wide variety of mechanisms of inclusion that go beyond direct involvement. In particular, Heeks et al. (2014) have developed a conceptual framework distinguishing 6 levels of inclusive innovation (see **Figure 1**).

Step 1, intention, entails the intention to address the wants or needs of certain groups, in this case smallholder farmers (Heeks et al., 2014). For crop gene editing, this raises the question what benefits the projects intent to bring to smallholder farmers, for example, by focusing on specific crops and traits. This is merely one way to achieve inclusion. For example, crops that were never intended for smallholder farmers can nevertheless end up benefiting them, while reversely, the intention alone does not guarantee that the crop will indeed have a positive impact.

Step 2, consumption, entails that the innovation is used by the excluded group (Heeks et al., 2014). In this research, the user of the crop is the smallholder farmer, who grows the crop and can either consume the crop or exchange it. Step 3, impact, entails the positive impact that innovation has on the livelihoods of the excluded group. This can refer to anything from economic productivity to welfare and from capabilities to health benefits. As gene editing crops are not yet available for farmers at this early stage, we capture both Steps 2 and 3 by identifying the plans projects have to achieve this.

Step 4, process, refers to the inclusion of smallholder farmers in the innovation process. For this step, Heeks et al. (2014) identified 2 substeps, one with forms and the other with moments of inclusion. The form of inclusion can range from being informed, to collaborating, to eventually controlling. The moment of inclusion can range from the initial plans all the way to the final distribution and evaluation of the innovation.

Step 5, structure, raises the question whether the structure of the innovation system—the institutions, organizations, and relations—is supportive toward innovations for excluded groups (Heeks et al., 2014). Research projects can, for example, take measures to build supportive structures for inclusive innovation, for example, in terms of policies and regulations, public support, skills and knowledge, and financial capital for inclusive gene editing. The highest step of the ladder, Step 6 poststructure, raises the question whether the frames of knowledge and discourse of key actors in the innovation system are inclusive (Heeks et al., 2014). At the most basic level, this includes questions about communicating in ways that create a level playing ground between innovators and smallholder farmers. Beyond that, poststructural inclusion concerns the various ways in which the innovation changes assumptions about the relation between innovation and innovation systems with smallholder farmers (Woodson and Williams, 2020).

The ladder is generally understood as a progressive framework: The higher the step on the ladder, the more inclusive the innovation. For example, an innovation at Step 1 is inclusive in terms of intent, such as a product designed to meet the needs of the poor; an innovation at Step 3 actually has a positive impact on the poor; and at Step 5, innovations make socioeconomic, institutional, or organizational structures of production more inclusive. In the discussion section, we will argue that achieving inclusion is not always clear-cut: Measures that some actors believe achieve inclusion may be contested by others. For our purposes here, the main strength of this framework is that it allows us to capture measures for inclusion beyond the direct involvement of diverse societal groups in the innovation process. This is only one step of the ladder (Step 4), only one way in which inclusion can be achieved. This framework thereby offers a broad perspective on the various ways in which inclusion can occur. As such, this offers a helpful basis for identifying inclusive innovation in crop gene editing for smallholder farmers.

3. Methodology and data

We focus on *research projects* as the unit of analysis for understanding inclusive innovation in crop gene editing. Projects are temporary organizations in which "a set of diversely skilled people working together on a complex task over a limited period of time" (Goodman and Goodman, 1976, p. 494). The focus on projects is especially suitable for studying research activities at an early stage of technological development. Only a handful of gene-edited crops have entered the market (Molteni, 2019), of which none are in the global South, and scientific articles often insufficiently articulate the envisioned relation of the academic work to smallholder farmers. As increasingly prominent organizational forms for coordinating and producing research (Steen et al., 2018), projects render such activities visible even before academic publications are published.

We used 2 criteria for selecting projects: The projects focus on crops that are specifically relevant for smallholder farmers, and the projects include smallholder benefits as one of their objectives. This implies that projects were excluded that do not explicitly state smallholder benefits as one of their objectives, even if they work on crops that are widely grown by smallholder farmers in the global South, like maize or potato. While these projects may theoretically yield outcomes that benefit smallholder farmers, these projects are unlikely to target traits that are exclusively useful for smallholder farmers or to take active measures to ensure the improved varieties are accessible to smallholder farmers. These criteria helped to ensure that all selected projects indeed use gene editing to improve food security for smallholder farmers in the global South. The rationale is that if inclusive innovation occurs anywhere in crop gene editing, then it is most likely to be in such projects.

The crops that are specifically relevant for smallholder farmers were identified by combining crops included in (1) the CGIAR list of "crops to end hunger" (2018), (2) the list of orphan crops for the developing world from Tadele's (2019) review of academic literature and the African Orphan Crops Consortium (n.d.), and (3) the list of cash crops covered in the Sustainable Smallholder Agribusiness Program (SSAB, 2021). These resources include crops based on different criteria. By compiling a list that combines all these crops, we ensure that we cast our nets widely in searching for gene editing projects that may benefit smallholder farmers. The CGIAR "crops to end hunger" predominantly includes food crops that were selected based on productivity for smallholder farmers, the SSAB list complements this by selecting for cash crops, and the list of orphan crops complements this by selecting for crops that have been little researched. As a result, these crops often produce inferior yields and thus are not part of lists including crops based on their productivity, yet these crops may nevertheless be hugely important for smallholder farmers. By combining crops mentioned on all lists, we can be reasonably sure that any gene editing project claiming to benefit smallholder farmers will be included. Smallholders were broadly defined as resource-constrained farmers who manage small plots of land, usually less than 10 hectares (FAO, 2012). The final list includes 138 different crops and can be found in Table S1.

The 2 selection criteria formed the basis for formulating search terms that were used to identify relevant research projects. We formulated a comprehensive set of search terms (see Table S2) that were entered in both academic search engines (Google Scholar and Scopus) and regular search engines (Google and Google News). The strategy was to first cast our nets widely by combining broad search terms and only then narrow down to more specific queries. For some crops, the number of publications found was too numerous to go through one by one. For example, combining "*Eragrostis tef*" and "genome editing" yielded less than 100 results that we all opened in search of relevant projects. But searching for CRISPR and maize yielded over 14,000 results. Therefore, those crop names were combined with additional terms to filter the results on projects with the intention to develop the crop for smallholder farmers in the global South.

In addition, we searched for projects in 9 recent review articles on crop gene (Jiang et al., 2013; Schaeffer and Nakata, 2015; Arora and Narula, 2017; Ricroch et al., 2017; Haque et al., 2018; Jaganathan et al., 2018; Chen et al., 2019; Han and Kim, 2019). In each of these articles, we selected all references to articles on crops that are relevant for smallholder farmers (using the same list discussed above) and looked for any projects that the authors were involved in. And, finally, we used a snowballing method by asking interviewees whether they knew any other relevant gene editing projects.

In total, we found 30 research projects around the world. We subsequently approached members of all 30 projects for an interview. Following the key informant technique, we first approached the project leaders of each of the project partners. These key informants have the best overview of the project activities and structure. We conducted 23 interviews with 24 interviewees of 18 different projects (see **Table 1**). In 2 interviews, the leader of project partner was not available, and instead, other team members were interviewed that were suggested by the project leader. The interviews took between 28 and 88 min and were conducted online in the spring of 2020.

Our approach allows us to capture the way inclusion is perceived by members of the different projects. This builds on the recent observation that actors may strongly diverge in how they interpret and seek to achieve inclusion at each step of the ladder, depending on the normative stance taken (Levidow and Papaioannou, 2017; Pansera and Owen, 2018). For this reason, we conducted semi-structured qualitative interviews. This interview technique allowed us to provide sufficient space for different interpretations to emerge of what it means to achieve inclusion. Our interview guide included a set of broadly formulated open questions about each step of the ladder of inclusion that allowed interviewees to interpret these steps from different normative stances. For example, for Step 3 on impact, some interviewees referred to increasing yield, while others spoke about reducing costs, improving health, or increasing quality of life.

All interviews were recorded and transcribed and were subsequently coded. Statements of interviewees were first categorized under the different steps of the inclusive innovation ladder. These statements were then coded in a more open way, finding differences and similarities in the ways that inclusion in the steps of the ladder were articulated and realized by different projects. These codes were subsequently analyzed by mapping what approaches to inclusion were and were not taken and by identifying patterns that could help to categorize the projects based on differences and similarities in their approach to inclusion.

4. Results

4.1. Is gene editing used for smallholder farmers?

In total, we identified 30 research projects that include smallholder benefits as one of their objectives and that work on crops that are specifically relevant for smallholder farmers. The projects are mostly conducted by public research organizations, and most projects are based in the global North. Of the 18 projects we interviewed, 2 projects are based in both the North and the South, and only 6 are entirely based in the global South (see **Table 1**). This

Table 1. Project overview

Crop	Trait(s)	Location	Interview	Type
Banana, coffee, and rice	Banana Panama disease resistance and low caffeine coffee	United Kingdom	5	
Cacao	Disease resistance	United States and Ivory coast	3, 19	
Cacao and cassava	Disease resistance, quality improvement, and lowering metal contamination	United States	11	
Cassava	Brown streak virus resistance	United States	16	
Cassava	Mosaic geminivirus resistance and new starch form	Switzerland and Belgium	1, 13	
Cassava	Lowering cyanide levels	United States	11, 12	
Cotton	Cotton leaf curl resistance	Saudi Arabia	15	
Cotton	Cotton leaf curl resistance	Pakistan	4	
Maize	Maize lethal necrosis tolerance	Mexico and Kenya	2, 21	
Oil palm	Ganoderma disease resistance and yield	Indonesia	18	
Oil palm	Ganoderma disease resistance	Indonesia	10	
Rice	Yield and water and nitrogen efficiency	Australia	20	
Rice	Cloning hybrid seeds	United States	6	
Rice	Bacterial blight resistance	Philippines and Germany	7, 8	
Rice	Salt tolerance	United States	22	
Rice	Disease resistance and bacterial blight resistance	United States	17	
Teff	Lodging resistance and grain size	United States	14	
Sorghum, pearl millet, cassava, teff, and maize	Disease resistance, quality improvement, and value-adding	United States	9, 23	

includes projects based in Africa (Ivory Coast and Kenya), Asia (Saudi Arabia, Pakistan, Indonesia, and Philippines), and Latin America (Mexico).

The projects focus on a variety of crops (see **Table 1**). Over one-third of the projects focus on rice (12 of 30), followed by several crops that are targeted by 3 projects (banana, sorghum, and cassava). Other crops were targeted by only 1 or 2 projects (maize, millet, cocoa, coffee, cowpea, cotton, oil palm, teff, beans, and tomato).

The projects also focus on a variety of different traits that can benefit smallholder farmers. The majority of the projects focus on traits for increasing yield (12 of 18). Most of these projects focus on improving resistance or tolerance to diseases and pests, but there are also projects that seek to increase yields by enlarging grain size or increasing lodging resistance and the efficiency of photosynthesis. Several projects also focus on other types of traits that are not directly related to yield. Two projects use gene editing to add value to the crops—by making cassava starch suitable for industrial processing and by increasing the quality of cacao, two projects target traits to improve crop health by lowering disease contributing elements in cassava, two projects attempt to improve the climate-resilience of rice by focusing on salt tolerance and water efficiency, and one project targets economic benefits for smallholder farmers by making hybrid varieties cloneable, thus enabling smallholder farmers to replant their seeds instead of having to buy new seeds.

Before having a closer look at how inclusive these projects are, it is worth briefly situating these findings in the broader crop gene editing landscape. This allows us to draw some tentative conclusions about the extent to which gene editing is currently used for smallholder farmers. First of all, these findings suggest that gene editing indeed can be used to target crops and traits that may benefit smallholder farmers. Gene editing is already used for various crops and traits that are relevant to smallholder farmers, including orphan crops like cowpea, millet, cassava, and teff, and including cash crops that are predominantly grown by smallholder farmers, like coffee and cocoa.[2] This is relatively diverse compared to the crops

2. And this only includes projects that explicitly seek to benefit smallholder farmers. Articles and projects that do not explicate the objective to target smallholder farmers are hence excluded while potentially benefitting smallholder farmers. This includes gene editing work on rice, cotton, tomato, banana, and sorghum (e.g., Bao et al., 2019). These crops are also grown by large farmers and on plantations, and it is difficult to disentangle to what extent these gene-edited crops benefit different farmers. But it is likely that at least some traits related to disease and pest resistance could also benefit smallholder farmers.

and traits that conventional genetic modification techniques were applied to in their early days of development. Even as recent as 2019, a stunning 98% of commercial crops that were modified with conventional genetic modification techniques consisted of only 4 crops: soybeans, maize, cotton, and canola (International Service for the Acquisition of Agri-biotech Applications, 2020).

The second tentative conclusion is that these findings also suggest that the use of gene editing for smallholder farmers is only emerging slowly. Thirty projects are relatively little when compared to the global crop gene editing research landscape. For example, already prior to 2018, several hundreds of gene editing patents were filed in the plant category (Martin-Laffon et al., 2019), and a brief Web of Science search yields over 2,000 CRISPR results for in the categories plant science, agronomy, and horticulture alone. Considering that small farms constitute an estimated 84% of all farms worldwide (Lowder et al., 2021), it seems that 30 projects that are explicitly dedicated to using gene editing for their plight are rather low. To be sure, juxtaposing these numbers merely gives an indication, but it at least suggests that the claim that gene editing is "accelerating research (. . .) [for] farmers in the developing world" (Gates, 2018) is excessive.

This can also be concluded by looking at the crops that are targeted. We found projects for only 11 of the 138 crops that are listed as requiring urgent improvements for smallholder farmers (see Table S1). While this demonstrates that gene editing in principle can be used for smallholder farmers, it also means we did not find gene editing projects for another 127 relevant crops, including crops that constitute an important part of smallholder farmers' production and diet in different pockets around the world, like papaya, okra, coconut, groundnut, and finger millet, to name a few. This corresponds to the findings of a recent article that crawled scientific publications and found gene editing was used for 22 orphan crops (Venezia and Krainer, 2021).

In addition, relatively few countries engage in gene editing for smallholders. Leading gene editing countries in the global North like the Netherlands, Japan, and France do not have a single project focused on smallholder farmers. And very few countries from the global South appear on the list. The projects include researchers from only 2 African countries, 1 Latin American country, and 4 Asian countries. This is corroborated by earlier findings on the distribution of CRISPR plasmids—an often-used tool for gene editing—which highlighted that CRISPR research is almost entirely absent in Africa and is only sparsely present in Asia and Latin America (LaManna and Barrangou, 2018).

Also notably absent are China, India, and Brazil. These countries have substantial numbers of smallholder farmers, already have GM crops on the market, and are actively using crop gene editing—China is responsible for over 60% of worldwide CRISPR patents for plants (Martin-Laffon et al., 2019). While it is certainly possible that researchers in these countries use gene editing for smallholder farmers outside of projects, or without explicitly talking about smallholders as their intended beneficiaries, there are also several indications that crop gene editing is mostly used for other purposes. China's agricultural research priorities, for example, explicitly steer toward large-scale industrial farming and away from smallholder farmers (Schneider, 2015; Si et al., 2019). At the very least, it can be concluded that projects in these countries do not explicitly formulate the objective to use gene editing for the benefit of smallholder farmers or farmers that are poor, marginalized, or resource-deprived.

In short, the systematic search yielded 30 projects that use gene editing for orphan crops with the objective to benefit smallholder farmers in the global South. This provides evidence for the claim that gene editing currently is used to improve crops that benefit smallholder farmers. The relatively small number of projects, the limited set of crops that are targeted, and the limited number of countries that are pursuing these objectives show this work is anything but substantial.

4.2. How inclusive is gene editing for smallholder farmers?

In the previous section, we have given a preliminary answer to the question of *whether* gene editing is used for smallholder farmers. In this section, we will describe how projects that state smallholder benefits as one of their objectives seek to achieve inclusion. Based on the semi-structured interviews, we have assigned the project activities along the lines of the ladder of inclusive innovation.

We found 2 different approaches to inclusive innovation for smallholder farmers. We call these spacecraft and helicopter approaches (see the icons in **Table 1**). Projects that take the spacecraft approach are by all accounts far removed from smallholder farmers. They identify smallholder needs without consulting with farmers and only plan to engage with smallholders after having fully developed new crops. In terms of the ladder of inclusive innovation, these projects were more or less inclusive in terms of intention, consumption, and impact (Steps 1–3) but much less on the 3 higher steps. We call this the spacecraft approach to capture the great distance between the projects and smallholder farmers and the lack of contact between project participants and smallholders for the duration of the project.

Projects taking the helicopter approach, in turn, operate much closer to smallholder farmers. These projects make several attempts to involve smallholder farmers in identifying research priorities, in conducting the research, and in disseminating the outcomes. These projects were more or less inclusive on all steps of the ladder of inclusive innovation. We call this the helicopter approach to capture that these projects are flying much closer to the soil and make stops to consult farmers more readily and more frequently. While we found a very clear distinction between projects taking helicopter and spacecraft approaches to inclusion, these differences were not correlated with any other factor that we coded for, such as the type of crop or trait, the objectives of the project, its geographical location, the type of actor and their collaboration, or the starting date of the project.

Because spacecraft and helicopter approaches were very similar at the first 3 steps of the ladder of inclusion, we will first discuss those 3 steps for both projects. Next, we will dive deeper into the differences between spacecraft and helicopter approaches at the higher steps of the ladder.

4.2.1. Steps 1—3: Intention, consumption, and impact

The first step of the inclusion ladder concerns intention. The great majority of the projects intend to benefit smallholders by focusing on crops that benefit the greatest numbers of farmers and on crops that benefit farmers in terms of food security and income. As a result, most projects focus on major staple and cash crops. For example, one researcher explained that they focused on rice "because rice (. . .) feeds over 3.5 billion people, half the world population" (Interview 22). Similarly, another project focuses on coffee because this "provides the main source of livelihood for about 125 million people globally" (Interview 5).

In a few exceptional cases, the choice of crop is also informed by technological and organizational considerations. One project, for example, collaborates with a large chocolate company and focuses on cacao because that is what they received funding for, and another project chose to work on rice because "it is really transformable" (Interview 6) with gene editing technologies. However, in terms of inclusion, the choice of crop is informed by the intention to include as many smallholder farmers as possible.

One implication is that less widely cultivated orphan crops are not targeted. The only exception to this rule is a project on teff—a crop that is mostly grown by smallholders in Ethiopia and Eritrea. In this project, the choice for teff was informed by an Ethiopian researcher who insisted on working on a crop for her home country. In all other projects, however, only those crops are selected that are perceived to benefit the greatest number of smallholder farmers and that benefits smallholders in terms of food security and income.

The same intentions informed the selection of traits: Most projects chose to work on those traits that can benefit large numbers of smallholders and that can specifically benefit them in terms of food security and income. As a result, about half of the projects work on traits for improving resistance to major pests and diseases, while traits for improving nutritional qualities or health impacts or cultural significance or storage ability are largely absent.

Remarkably, not a single project directly consulted smallholder farmers in selecting crops or traits (which we will discuss in greater length under Step 3). About a quarter of the projects identified relevant traits based on discussions with collaborating scientists in the global South. For example, one scientist working on rancidity in pearl millet "hadn't really thought about focusing on rancidity," but their Indian collaborator "called it [rancidity] the main challenge for smallholder farmers in India" (Interview 24). Most other projects, however, identified the crops and traits based on issues that are supposedly "widely known." When asked how they identified the problem they work on, one interviewee answered rather surprised: "Oh, that problem has been identified by the field many years before I started my PhD" (Interview 1). This is in line with findings from earlier studies that have shown that scientists rarely consult farmers, assume to know the challenges farmers face, and subsequently focus on yield and income (James and Sulemana, 2014).

The second step—consumption—concerns both the type of user or consumers who are targeted and the strategies to ensure these consumers are reached. Also at this step, most projects took a rather similar approach to inclusion. Given the projects were selected for their focus on smallholder farmers, it should come as no surprise that smallholders were the main target group. Smallholder farmers are an incredibly diverse group though. Generally referring to farmers who own relatively small portions of land, this includes farmers from a variety of backgrounds (in terms of education, gender, class, caste, etc.), in diverse ecosystems and operating in highly diverse farming systems (ranging from subsistence farming without external input to growing cash crops for well-developed markets). Yet, with the exception of one project, no project specified this any further, for example, by focusing on female farmers, agricultural laborers, or smallholders with specific ethnic or cultural backgrounds.

The only exception concerns a project that specifically targets female farmers because these were considered a disadvantaged group that especially stood to benefit from improved crops. Most other projects, however, indicated that they had not yet thought about a more specific target group. When asked about what type of smallholder they were targeting, one interviewee simply noted "I have no clue about that, for us it is [smallholders] in general" (Interview 6). This undifferentiated view of smallholder farmers may be a result of the failure to include smallholder farmers in the early stages of the innovation process, as will be further discussed under Step 4. In the absence of such inclusion, it should not come as a surprise that ideas about smallholders "in general" resulted in projects that focus on crops and traits that benefit the greatest number of smallholder farmers. Crops and traits that benefit specific subsections of smallholder farmers remain understudied.

The projects take various measures to ensure their crops will reach smallholder farmers. For one, interviewees in 6 projects indicate that their crops will be made available "at a very low cost" or at least not above market prices, and 4 interviewees explain that the crops will be practically free (Interviews 1, 10, 11, and 14). The practical details of these plans are rather vague; however, as interviewees note, this depends on financial aid to cover the gap between costs and market price.

In addition, all projects plan to distribute the crops to farmers by collaborating with actors in established seed systems in the global South. All projects plan to collaborate with government actors and make use of their extension systems, for example. "The governments know where the farmers will be able to be reached" (Interview 1), as one interviewee told us. In addition, 5 projects have set up collaborations with companies in the global South who "will bring the seed to the farmer" (Interview 20), and 3 projects plan to "piggyback" on activities carried out by the CGIAR institutes, as these "are already set up to provide germplasm" (Interview 11) and are thought to "have an intimate relationship with smallholder farmers" (Interview 23).

While this strategy has practical benefits as the development of new seed systems may go beyond the scope of gene editing projects, the reliance on existing seed systems also has limitations. Many smallholder farmers around the world largely rely on informal seed systems (McGuire and Sperling, 2016) and thus cannot be reached via the channels mentioned above. Five projects explicitly recognize these limitations and take measures to address them. Two of these projects plan to disseminate seeds via informal seed systems, and 3 projects plan activities to improve seed systems in countries where the system is inadequate (Interviewees 8 and 9). For example, one project sets up collaborations with small shops in the Kenyan countryside to sell small packages of improved seeds in order to reach smallholder farmers who are generally not well-served by markets (Interview 2).

The third step of the ladder covers the actual impact that the innovation has on smallholder farmers. Because none of the projects have as of yet brought varieties to the market, we will discuss the intended impacts here. This strongly overlaps with Step 1—intention—so we will be brief. The main impacts on the inclusion of smallholder farmers were expected to be increases in economic prosperity and food security.

The impact on income is targeted in 3 ways: by increasing yields, reducing costs, and adding value to the crops. Yield increases can positively impact income from crops that are sold on the market. For example, a project on cassava explains their goal as "to improve the yields for the farmers so that farmers who grow cassava have a higher income" (Interview 1). Cost reductions are mostly achieved by robust developing crops that require less external inputs. Another interviewee, for example, notes that spraying only 50% of the previous amount of pesticides will reduce production costs (Interview 4). And adding value to the crop can also increase income. For example, crops with improved quality or flavor allow farmers to ask higher prices (Interviews 3 and 9), and changes in other traits may create new market opportunities (Interviews 1, 9, 13, and 14). For example, several interviewees point out that altering the starch content of cassava can make this crop suitable for the starch industry, which could increase the price of cassava.

Food security, in turn, is aimed for by improving yields and reducing risks. For the former, Interviewee 7 explains that improved yields of maize can impact 70% of the Kenyan population involved in farming. He said: "think of that many people getting a boost in productivity [. . .] it can be very meaningful for food security for these countries." For the reducing risks, Interviewee 16 explains the importance of resistance to cassava brown streak disease. Many SHFs use cassava as a backup for food, as you can leave it in the soil for an indefinite period. Taking away risks of crop failure, thus, also improves food security.

About half of projects also seek to achieve other inclusionary impacts besides income and food security. For example, 7 interviewees note that higher incomes increase the chances that children receive education. About half of the projects note that gene-edited crops can positively impact the quality of life of smallholders, for example, by improving health as a result of reduced pesticide sprayings (Interviews 11 and 16) and by reducing the need for hard labor as a result (Interviews 3, 4, 9, 12, and 14). These impacts are mentioned less prominently, though they are formulated as indirect benefits of the objectives to increase income and food security, and no specific measures were identified to achieve impacts.

Overall, with a few exceptions, all gene editing projects include smallholder farmers by targeting crops and traits that benefit the largest numbers of smallholder farmers (Step 1), disseminating these crops via existing seed systems in collaboration with governments, companies, and CGIAR institutes (Step 2), in order to increase income and food security of smallholders (Step 3). The projects, hence, show remarkable uniformity in the way gene editing is innovated inclusively. This is all the more remarkable considering there are many other possible ways to achieve Step 1 intention (building capacity in the global South, focusing on historically disadvantaged groups like women or lower castes), Step 2 consumption (focusing on specific subsets of smallholders, distribution via informal seed systems, and developing new seed systems), and Step 3 impact (adding nutritional value, minimizing health risks, and reducing labor requirements).

When it comes to Steps 4–6, less uniformity was found. Instead, we found that projects take 2 very different strategies for innovating inclusively.

4.2.2. Steps 4—6: Spacecraft projects

The first cluster of projects that we call "spacecraft projects" does not take substantial measures to innovate inclusively in terms of process (Step 4), structure (Step 5), or poststructure (Step 6). As such, these projects are far removed from smallholder farmers themselves: The projects do not consult farmers (Step 4), only take a few measures to create a favorable infrastructure for smallholders (Step 5), and do not include the frames of knowledge and discourses of smallholders in their activities. Because of this distance, we propose to call such projects spacecraft projects, where innovation is conducted far "from the ground."

The inclusive innovation ladder notes that smallholder farmers could be included in the process (Step 4) either lightly by consulting them at the start of the project, more radically by giving them full control over the innovation process, or anything in between. In the case of spacecraft projects, the only evidence for including smallholder farmers in the process is in the form of plans to inform farmers of the results in the future, once the projects are near to completion. This can be categorized as the lowest step of process inclusion.

The decision not to include smallholders in early phases of the project is justified by noting that these technical phases of the project do not allow for such involvement. "We haven't got to that point where we can involve farmers," one interviewee noted, because "it's still at the technology development stage" (Interview 6). Smallholder farmers can only be included, so interviewees note, "when you have something in hand" (Interview 15) or once the technology is more than 95% efficient (Interview 6). Another interviewee similarly notes that they have not yet contacted farmers themselves, "because we still try to finish the technology" (Interview 10). Only once the technology is finished, do the projects plan to include farmers, for example, by involving them in field trials or in spreading seeds (Interviews 6 and 10).

The fifth step of the inclusion ladder concerns efforts to create a favorable structure for gene editing research to benefit smallholder farmers, including, for example, a regulatory environment that favors inclusive gene editing, capacity building activities, or institutional infrastructures that support collaborations for inclusive gene editing. Also, for this step of the ladder, spacecraft projects only take very few measures. Most of these concern activities to develop a technological infrastructure that could benefit smallholder farmers. For example, all but one spacecraft project actively seek to share their technology and technical know-how with scientists outside of the project, for example, by attending scientific conferences and discussing their findings with other researchers. And most projects also seek to tackle potential barriers that may arise from intellectual property rights over their work. Some spacecraft projects decided not to apply for patents at all (Interviews 10 and 15), while others apply for patents but will not enforce these for smallholder applications (Interviews 6, 16, and 20).

Aside from these measures for technological infrastructures, other measures were fragmentary and small. Capacity building in these projects was limited to training students and researchers in the projects itself and was generally not an objective in itself. And while one spacecraft project engages in conversations with a national government to shape regulations, in all other cases, the researchers took a passive stance toward such activities, noting that "lobbying for regulations is not the role of scientists" (Interview 6), that this only happen in later phases, or that they are not invited to "such official meetings."

Also for the sixth step of the ladder—poststructural inclusion—very few measures were found. This concerns measures such as the inclusion of smallholder knowledge, communication in languages spoken by smallholders, and including smallholder considerations in the wider goals of the organization. Spacecraft projects only show very limited inclusion on all 3 aspects. This should not come as a surprise, considering that spacecraft projects do not consult farmers to acquire their knowledge in the first place (Step 4 process). Yet, it still stands out that, with one exception, no measures were taken to communicate results in languages other than English, and that generally, the inclusion of smallholders does not have a strong impact on their organizations' goals. Interviewee 16, for example, explains: "To be honest, I think the majority of the people here [. . .] are trying to answer some basic science questions that could have implications for improving agriculture in general."

4.2.3. Steps 4—6: Helicopter projects

Contrary to spacecraft projects, the second cluster of projects does include smallholder farmers early on (Step 4 process), takes more steps toward structural changes for inclusion (Step 5 structure), and includes farmers' knowledge (Step 6 poststructure). Rather than being far removed from smallholder farmers and only interacting with them once the project is finished and the spacecraft has landed, these projects interact with smallholder farmers at different moments throughout the process. To capture these movements between scientific research and smallholder farmers, we propose to describe these projects as helicopter projects, in keeping with the aircraft metaphor.

Helicopter projects include smallholders in various moments throughout the projects (Step 4 process). Like spacecraft projects, helicopter projects plan to engage farmers in field trials once the product is finished (Interviews 12, 14, 19, and 20). However, helicopter projects also include farmers at an earlier stage. The majority of the projects regularly visit smallholder farmers on their farms (Interviews 1, 5, 8, 13, 17, 18, 19, 21, and 22), and several events are organized that are dedicated to engage with smallholder farmers, including field days (2 and 21), farmer field schools (19 and 21), education workshops (3), social gardens and agricultural fairs (21), farmer days (4), and even participatory breeding activities (19).

Several helicopter projects use these activities to inform farmers about their work early on (Interviews 1, 2, 5, and 21), something spacecraft projects deem useless as long as the end product is not finished. But more importantly, the helicopter projects also use these activities to listen to smallholder farmers and incorporate their views into their work. For example, several interviewees describe how visits to farmers' fields enabled them to ask a wide range of questions to farmers. One interviewee working on cassava describes that "at one farm that we visited, we would ask them what they were growing, how their field was set up, and (. . .) whether they had severe pressure for the virus on their cassava plants" (Interview 1). Another interviewee notes that "I usually ask about management practices they use (. . .) [and] I am always interested in how much they harvest, which varieties they grow, and how they reach markets, and if they've grown for their own consumption or for other purposes" (Interview 8). Farmers were thus not only included by asking them about what traits most benefit them but also about wider aspects such as farming practices and market access. Moreover, several helicopter projects collect information from farmers by conducting surveys (Interviews 1, 7, and 9) and by collaborating with local partners who "talk to hundreds of farmers" (Interview 9).

All helicopter projects indicate that these insights are used to inform their project work and ensure that suitable crops are developed (Interviews 1, 2, 4, 7, 9, 13, 14, 17, 21, and 22), for example, in designing the product or prioritizing some traits over others (Interviews 4, 7, 9, 13, 21, and 22). None of the projects give formal control of decision-making power to farmers—the highest substeps in the framework. Yet, the interviewees seem to be keenly aware of their distance to smallholder farmers and of the need to make an effort to include farmers and take them seriously. One interviewee notes: “If you just go and lock yourself somewhere and develop a product, then you go to the people, then you will be surprised because yes, you have a very good product, but that is not what they want” (Interviewee 21). Similarly, another interviewee indicates that continuous contact with farmers is necessary in order “to make sure that we are developing the right types of products” (Interviewee 5).

None of the projects started with including smallholder farmers, however. This is quite a severe limitation to the inclusiveness in terms of process: Several decisive elements in making gene editing relevant for smallholder farmers had already been decided upon long before smallholder farmers were involved in the projects, such as the type of crop that the projects would work on and the trait that they would target.

As for Step 5 of the ladder—structure—helicopter projects seek to increase public support by giving talks and appearing in the media, and helicopter projects also abstain from patenting their technology or from enforcing their patents for smallholder applications, just like spacecraft projects. Yet, helicopter projects also take various other measures for an inclusive structure. For example, about half of the helicopter projects regularly provide information about gene editing to regulatory bodies at both the national and international level, almost all helicopter projects share the outputs of their research by presenting at conferences in the global South, and 3 projects even openly share genes, varieties, and vectors with other researchers in the global South.

Moreover, helicopter projects take various steps to build gene editing capacity in countries in the global South. Almost all helicopter projects, for example, organize training workshops, lectures, and seminars in the global South and create training programs in developed country institutions that were specifically targeted at students and researchers from the global South. In the long term, these efforts seek to enable global South scientists to conduct gene editing research themselves, “to launch their own programs, their own research” (Interview 13).

Several other measures for promoting structural inclusion that the theory suggests were not found. For example, no measures were taken to create an institutional infrastructure that would be more beneficial to smallholder farmers. For measures to promote more inclusive financial infrastructures, we only found 1 example, in a project where a private company gives grants to researchers to work on the orphan crop teff. One other project mentioned crowdfunding as an alternative way to generate more inclusive financial infrastructures, but the project itself did not contribute to that. Nevertheless, compared to spacecraft projects, helicopter projects take much more measures to realize structural inclusion.

The same is true for the highest step of the ladder—Step 6 poststructure. Here too, the helicopter projects only do a limited number of activities that are suggested by the ladder of inclusive innovation, yet the helicopter projects do take several actions to ensure poststructural inclusion and as such are more inclusive than spacecraft projects. About half of the helicopter projects, for example, make dedicated efforts to communicate their findings in local languages of smallholder farmers. In addition, the majority of helicopter projects are embedded in organizations that themselves have the goal to benefit smallholder farmers or to improve agriculture in the global South. And finally, as was already alluded to under Step 4, the majority of the helicopter projects also incorporate knowledge of smallholder farmers in their project. One project notes that this, for example, includes “knowledge about what varieties are popular in that country (. . .). This is not really published knowledge; this is more informal knowledge that came from talking to farmers” (Interview 1).

Farmer knowledge was collected via the various steps of including smallholder farmers that were discussed under Step 4 process, for example, by collaborating with local partners “who go and talk to farmers all the time” (Interview 12) or by visiting farmers themselves and conducting surveys. The projects display a genuine interest in taking farmer knowledge seriously, noting that capturing farmer knowledge “is needed to succeed at the end of the day” (Interview 7). Yet, it became clear from the interviews that the poststructural changes are rather limited, especially as farmer knowledge was often treated as an important add-on, but it was not always treated on equal footing with other types of knowledge. The projects still “mostly use scientific knowledge” (Interview 2), and “scientific, published work, is our primary knowledge base” (Interview 1). Nevertheless, compared to spacecraft projects, the helicopter projects are each characterized by taking various measures for including smallholder farmers in terms of process (Step 4), structure (Step 5), and poststructure (Step 6).

5. Discussion

In the previous section, we have presented 2 main findings with regard to the potential of gene editing for smallholder farmers in the global South. First, the projects we found support the claim that gene editing indeed is being deployed to improve orphan crops for smallholder farmers in the global South but that this does not happen much yet. Second, we found these projects take 2 different strategies toward inclusive innovation (see **Table 2**). What we call spacecraft projects were inclusive in terms of the first 3 steps of the ladder of inclusive innovation—intention, consumption, and impact—while failing to be inclusive in terms of process, structure, and poststructure. What we call helicopter projects attempted (some) efforts at inclusion on all steps of the ladder.

The ladder of inclusive innovation provides a valuable framework that served as the basis for identifying 2 distinct approaches taken by gene editing projects. Importantly, however, we would like to warn against taking a “checkbox approach” in using the ladder of inclusive innovation. Merely undertaking activities on each step of the ladder does not imply that inclusion has been

Table 2. Overview of inclusive innovation measures of spacecraft and helicopter projects

Ladder of Inclusion Steps	Spacecraft Projects	Helicopter Projects
1. Intention	Focus on widely known issues or issues their global South collaborator knew about.	
	Choose crops and traits based on impact on food security and smallholder income.	
	Aim to develop improved crop (and some helicopter projects aim at capacity building).	
2. Consumption	Target smallholders in general. Some projects target women or specific countries.	
	Reach smallholders via existing governmental, local company, or CGIAR systems.	
	Make crops affordable by offering them for free or at average market price.	
3. Impact	Improve food security and increase income by improving yields, decreasing risks of crops failure, and adding value to crops.	
4. Process	Inform smallholders once crop is finished.	Inform smallholders once crop is finished.
		Regularly consult smallholders, including early in the innovation process to inform crop design.
5. Structure	Some do not apply for patents or do not enforce this for smallholder applications.	Do not apply for patents or do not enforce patents for smallholder applications.
		Shape regulation in global South.
		Increase public support.
		Build gene editing capacity in the global South.
6. Poststructure		Incorporate smallholder knowledge.
		Organizations have inclusive goals.
		Communicate in smallholder languages.

sufficiently and successfully achieved. Several commentators have taken an issue with this approach by pointing out that what inclusion means is itself contested (Levidow and Papaioannou, 2017; Pansera and Owen, 2018; Opola et al., 2021). For example, actors may disagree over what the needs of marginalized communities are (Step 1) or what constitutes a positive impact (Step 3). Hence, the mere observation that projects are active on several or even all steps of the ladder does not negate the contested nature of inclusion.

We would like to propose that the ladder of inclusive innovation can instead best be used as a starting point for discussing what types of inclusion are most suited for the specific contexts and innovations at hand. By offering transparent insight into what steps are taken toward inclusion, how these steps are taken, and what steps are *not* taken, the ladder of inclusive innovation offers a starting point for a more meaningful reflection on how inclusion can best be achieved.

From this perspective, the value of the framework not only resides in showing what measures have been taken but also in showing what other steps could have been taken instead. In our analysis, this is most obviously the case in showing that spacecraft projects do not innovate inclusively in terms of process, structure, and poststructure. But this is also the case at the level of individual steps of the ladder. Our analysis, for example, also shows that the measures that were in fact taken for certain steps only constitute a limited set of activities that could have been undertaken for those steps. For example, both spacecraft and helicopter projects have the intention (Step 1) to benefit the largest number of smallholder farmers by focusing on crops and traits that are beneficial for a wide range of different smallholder farmers. This may go at the cost of focusing on traits that are especially relevant for specific subsets of smallholders, like female farmers, landless laborers, or farmers from low castes.

Similarly, both project types strive to impact (Step 3) smallholder farmers in terms of income and food security. This too is not a neutral choice. Here, too, projects could have very well targeted other inclusive impacts, like increasing farmer health by improving the nutrient content of subsistence crops or by diminishing the need for spraying harmful pesticides. These activities now largely remain undone. This is not to suggest that more inclusion activities are always better—projects and researchers can only do so much. However, by rendering these choices explicit, the inclusive innovation ladder can help to further decision making on how to best achieve inclusion.

To further this purpose, we propose to add an additional layer of analysis to the ladder of inclusive innovation in the form of different approaches to distributive justice. Specifically, we propose to draw upon the distinction between approaching distributive justice in terms of equalization, fairness, and pro-poor that was first developed by Cozzens (2008) and later refined by Smallman and Beumer (2022). Equalization concerns measures that target socioeconomic structures to reduce inequality, such as labor market measures to prevent job losses for low-income groups or models of ownership and intellectual property that have equalizing effects. Fairness, secondly, concerns measures to eliminate horizontal inequality, that is, inequalities along the lines of culturally defined differences, such as gender, ethnicity, or religion (Cozzens and Wetmore, 2010). And pro-poor, finally, concerns the creation of conditions in which products and services are developed that address the needs of the poor. By categorizing the activities on each step of the ladder within different approaches to distributive justice, we can offer a more refined understanding of the types of inclusion that have been achieved and the types of inclusion that have been neglected.

We have performed this analysis for the different gene editing projects as well (see Table S3). What we found is that gene editing projects overwhelmingly take a pro-poor approach: The inclusion measures were almost all targeted at creating products that could benefit the poor and to facilitate the effective dissemination of these products once finished.

The emphasis on pro-poor measures is itself not surprising, considering the projects' focus on gene editing for smallholder farmers. The absence of other distributive justice approaches is surprising, nonetheless, as gene editing can easily lend itself to such approaches. For example, we only found 1 project that combines pro-poor measures with a fairness approach by specifically targeting crops for female farmers, and we found no projects that focus on the needs of specific ethnic groups, castes, or landless laborers—groups that each face additional challenges to inclusion. Compared to men, female farmers, for example, work longer hours, conduct more labor-intensive tasks, earn less, and are more often paid at piece rate (Farming First, 2012). Gene editing could play a role in addressing these challenges, but these risks are being overlooked by focusing on smallholder farmers in general and by targeting groups that benefit the greatest numbers of smallholders more specifically.

We did find some more measures to achieve equalization. The focus on smallholder farmers (Step 2) itself could partly be understood as an equalizing approach itself, as increasing their income and food security could then result in a changing socioeconomic structure. But this was never articulated as a goal itself. Helicopter projects also take several other measures to change socioeconomic structures, for example, by developing seed systems to ensure the new crops can reach smallholders (Step 3), building research capacity for crop gene editing in the global South (Step 1), and effectively training researchers in the global South in various ways (Step 5). This addresses an unequal socioeconomic structure where research and development is concentrated in high-income countries that subsequently are in a better position to define research priorities.

In addition, most projects either decide not to apply for patents or plan not to enforce patents for smallholder applications. This addresses the challenge of accessing the innovations that is commonly hindered by existing socioeconomic structures, though these measures hardly change these socioeconomic structures itself. And a handful of projects plan to make the gene-edited crops themselves available for free, thus addressing socioeconomic structures that may prevent smallholders from accessing seeds on commercial markets. However, these plans remained rather abstract. In general, however, the equalizing measures taken by the projects are rather dispersed and piecemeal. This stands out because like in the case of fairness, gene editing easily lends itself to more far-reaching equalizing approaches, such as measures to promote the integration of farmers into value chains, to challenge the structure through which research priorities are set and the systems by which crops are valued.

6. Conclusion

Gene editing technologies are breathing new life into expectations about the benefits of GM crops for smallholder farmers in the global South. In this article, we have made a first attempt at putting these expectations to the test, in particular, by critically scrutinizing the inclusive nature of crop genome editing for smallholder farmers. Starting from the assumption that innovation in crop gene editing needs to be inclusive for it to benefit smallholder farmers, we have interrogated both *whether* crop gene editing is indeed employed for smallholder farmers and *how* this is done in ways that are more or less inclusive.

We identified 30 projects around the world that use gene editing with the objective to benefit smallholder farmers in the global South, including projects that work on orphan crops like cowpea, millet, cassava, and teff and cash crops such as coffee and cocoa. This provides evidence for the claim that gene editing currently is used to improve crops that benefit smallholder farmers. However, the number of projects is relatively small, the set of crops that is targeted is relatively limited, and the number of countries that engage in these activities is small. At the very least, the claim that gene editing is "accelerating research (. . .) [for] farmers in the developing world" (Gates, 2018) is excessive.

We also found that projects that do use gene editing for smallholder farmers approach inclusion in 2 different ways (see **Table 2**). What we call spacecraft projects innovate inclusively only on the first 3 steps of the ladder of inclusive innovation—intention, consumption, and impact. These projects conceptualize the needs of farmers in a rather homogenous way and in utilitarian terms—in terms of yield and income for the greatest number of farmers. Farmers themselves are not involved in the innovation process, and little is done in terms of inclusion at the higher steps of the ladder.

What we call helicopter projects took a more ambitious approach to inclusion and also took various measures to innovate inclusively on the highest three steps—process, structure, and poststructure. These projects, for example, took farmer knowledge seriously, gave farmers a voice in prioritizing crops and traits, and took some measures to create more favorable socioeconomic structures for smallholders, albeit in a very limited way as well.

Taken together, the picture that emerges is mixed at best: There are *some* projects that use gene editing to benefit smallholder farmers, but not many; these projects take *some* measures to innovate inclusively, but not many.

Considering these projects were selected for their focus on smallholder farmers, we posit that it is highly unlikely that the broader crop genome editing landscape is innovating inclusively.

These findings confirm the starting point that the inclusive innovation framework offers a fruitful starting point for thinking about inclusion in ways that go beyond direct engagement of "mini-publics." The framework helps in rendering visible a wide range of activities that further inclusion. To be sure, this includes activities for engaging smallholders but also other includes various other activities like improving crops or abstaining from patents. Even if spacecraft projects would actively engage smallholders, their innovation activities would still not be fully inclusive.

At the same time, we would like to reiterate the argument (Levidow and Papaioannou, 2017; Opola et al., 2021) that the framework should not be used as a checkbox: The mere fact that some activities can be identified at one or every step of the ladder does not necessarily mean that inclusion has been achieved. The basic observation that there are limits to how innovations can be developed and what their impact can be means that choices have to be made as to who is included and who stands to benefit (and who does not). As a result, inclusion could always be achieved in different ways, and inclusion thus inevitably remains open for contestation.

The value of the framework instead lies in rendering visible the choices that have been made in innovating inclusively: not only in innovating inclusively or not but also in innovating inclusively in some ways rather than others. This opens up such choices for critical scrutiny. To further this objective, we propose to supplement the ladder of innovation with different approaches to distributive justice. In the case of crop gene editing, such an analysis highlighted that projects predominantly take a pro-poor approach to inclusion and largely ignore equalizing and fairness approaches. Our inclusive innovation approach complements other recent attempts to broaden the ex ante assessment of the potential impacts of GM crops, such as those by Beumer (2019) and Schnurr and Dowd-Uribe (2021). Conventional assessments of GM crops' benefits have long prioritized yield measurements, often using experimental field data and early farm trials. This is limited in both the types of benefits that are measured, the distribution of such impacts across different contexts, and the types of knowledge that are included (also see Glover, 2010b). In response, Schnurr and Dowd-Uribe (2021) argue that the impacts of GM crops can be better gauged by evaluating crops for their alignment or incongruences with the farming systems they are designed to benefit, thus requiring a more context-specific assessment of GM crops' potential. Conventional assessments of GM's downsides, in turn, have been similarly restricted, having prioritized phytosanitary risks and risks to human health, while ignoring broader socioeconomic implications that GM crops may have. In response, Beumer (2019) and others have proposed different models of assessing such implications in sufficiently objective ways.

Both studies "open up" the assessment of GM crops to a broader set of contexts, values, and knowledges for specific crops. The inclusive innovation approach suggested here contributes to these efforts by opening up the earlier phases of the innovation process, before a crop has been developed, including decisions on the types of crop and traits that will be targeted in the first place. By suggesting different avenues for including smallholder farmers in this process, and by providing a framework that can entice reflection these choices, we hope to contribute to democratize agricultural biotechnology (Jasanoff, 2007; Montenegro de Wit, 2020).

Data accessibility statement

This study is based on interview data which are subject to human subjects' protection requirements. Please contact the authors for further information.

Supplemental files

The supplemental files for this article can be found as follows:

Table S1. List of crops for smallholder farmers. Docx

Table S2. Search terms. Docx

Table S3. Distributive justice approaches of gene editing projects for smallholder farmers. Docx

Competing interests

The authors declare no competing interests.

Author contributions

- Contributed to conception: KB.
- Contributed to acquisition of data: SdR, KB.
- Contributed to analysis and interpretation of data: SdR, KB.
- Drafted and/or revised the article: KB, SdR.

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