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Linking Upstream Genomics Research with Downstream Development Objectives:

The Challenge of the Generation Challenge Programme[1]

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ABSTRACT: This article discusses the work of the CGIAR Generation Challenge Programme (GCP), which researches genetic mechanisms of drought tolerance in crops in order to contribute to agricultural development for resource poor farmers in arid regions. Against the background of pleas for contextualized agro-technology development and bottom-up innovation processes, the question is asked how a relatively upstream scientific research programme can meaningfully contribute to local agricultural development and poverty alleviation. The article concretely evaluates the process of priority setting by the GCP and the operationalization of an innovation chain perspective, aimed at making sure that the outputs of GCP research are actually taken up by downstream research partners. Adopting a systems of innovation perspective, the potential for complementary innovation systems is explored in order to meaningfully link upstream science-led genomics research and downstream bottom-up breeding programmes. This exploration address the various partnerships of the generation challenge programme, as well as the Genotyping Support Service (GSS) as a specific technical interface between upstream genomics research and downstream variety development. This initiative is taken as a potentially interesting approach to agro-technological development that shifts focus from the development of a technical solution, to the provision of a technical service.

INTRODUCTION

This article discusses the work of the Generation Challenge Programme (GCP) of the Consultative Group on International Agricultural Development (CGIAR). The Generation Challenge Programme aims to uncover the genetic mechanisms of drought tolerance in crops, and as such hopes to contribute to agricultural development for resource poor farmers in arid regions. This article investigates the relationship between the upstream genomics work the GCP is doing, and its ambition to meaningfully contribute to agricultural development and poverty alleviation.

Global agricultural development is of ongoing high priority in international development debates, focused on the alleviation of extreme poverty and the eradication of hunger. The development of new crop varieties with higher yields, and increased resistance against with biotic (diseases, pests) and abiotic (drought, frost, soil toxicity) stresses is widely recognized to be a potentially useful way to contribute to agricultural development (Delmer 2005). The contemporary revolutionary pace of innovation in genomics, marker assisted breeding and biotechnology provides a background in which there is a lot of scope for improving existing crop varieties, and addressing some of the most pressing problems that farmers are coping with (Conway 1997). However, while the technical potential to adapt crop varieties to new needs or circumstances may be increasing, that does not automatically mean that molecular biology and plant breeding are able to solve real problems of resource poor farmers. Innovations may never reach farmers, may be prohibitively expensive, or may solve only a very limited part of the problem that people are facing 'in real life'. This observation leads to an interesting debate on how to make sure that the potentially revolutionary power of modern genetic technologies can actually contribute something to the needs that resource poor farmers in developing countries have, and the problems they face (Tripp 2001; Byerlee and Fisher 2002; Chataway 2005; Reece and Haribabu 2007).

In this debate, it is commonly recognized that not any technology that is successful in agriculture in developed countries, can simply be parachuted into a farming system in a developing country, and be expected to work. Instead, a notion of 'appropriate technology development' has become crucial in international development debates, drawing attention to the fact that technologies and development projects need to be adapted to the specific problems at hand, and the circumstances in which a technology has to work (Bunders 1988; Bunders and Broerse 1991; Art 1993).

One key element that emerges in this debate is the tension between an externally planned and executed modernization process, and bottom-up participatory development processes. Critical scholars of agricultural development and biotechnology have focused on the transformative nature of agricultural modernization, and have observed how in the past diverse local agricultural practices and farming systems have largely been replaced by a relatively homogeneous farming system (Kloppenburg 1988; Scott 1998; Ruivenkamp 2003, 2005; Van der Ploeg 2008). While this may have allowed productivity increases in some areas and for some farmers, this approach is argued to reach the limits of its validity in regions with different climatic and environmental conditions, which are traditionally characterised by highly diversified and locally adapted farming practices (Richards et al. 2009). This argument is specifically illustrated by the experiences with the Green Revolution, in which a relatively homogenized package of new crop varieties, and farming practices increased overall cereal productivity in many developing countries, but the effects of which have been highly unevenly distributed (Dixon 1990; Evenson and Gollin 2003).[2] Shifting focus from raising overall productivity to reaching farmers in marginalized areas and contributing to poverty alleviation, the question is raised how agricultural development can take local diversity in farming systems as starting point, and link up with already available local expertise, experience and resources. This may materialize in a renewed attention for peasant based production systems (Van der Ploeg 2008), linking up formal with informal seed systems (Louwaars 2007), the potential for endogenous development as opposed to externalized development (Van der Ploeg and Long 1994), the possibility of increased stakeholder involvement in agro-biotechnology development (Broerse 1998; Broerse and Bunders 2000), and the potential of tailor-made biotechnologies (Ruivenkamp 2003, 2005).

[2] 'Green Revolution' is the name that was given to a process of agricultural modernization in developing countries, most notably in the 1960s and 1970s. It was aimed at the increase of agricultural productivity, and depended upon a combination of improvements in infrastructure and research capacity, and the transfer and introduction of relatively simple agricultural technologies. These novel agricultural technologies included modern high yielding varieties (HYVs) of rice and wheat, and a package of agricultural tools and practices, such as the use of chemical fertilizers, irrigation and pesticides. See (Parayil 2003) for a useful introduction to the Green Revolution, and a comparison with the more recently emerging 'Gene Revolution'.

These initiatives and visions emphatically focus on the importance of setting local priorities in agricultural development, on contextualizing technology development, and on the importance of involving local stakeholders and making use of their expertise and creativity in development processes. The question that arises is what the implications are of this strong focus on contextualized technology development for the institutional organization of technology development projects. In other words, the question is whether appropriate biotechnology development essentially requires a local and bottom-up innovation process – implicitly disqualifying any science-led upstream research programme for the resource poor – or that upstream research can in fact provide a meaningful and 'appropriate' contribution to local innovation processes, without prescribing an externally formulated model of agricultural development.

This question is extremely relevant in the context of ongoing efforts to use upstream biotechnology and genomics research for agricultural development for resource poor farmers. One of these initiatives is the aforementioned Generation Challenge Programme. The work of the Generation Challenge Programme is primarily focused on comparative genomics research, and the understanding of genetic mechanisms for drought tolerance in crops. As such, most activities of the programme are rather upstream and relatively far away from the development of concrete new crop varieties. Still, the programme does have very concrete objectives and ambitions in terms of producing outputs that are relevant for resource poor farmers, and that contribute to poverty alleviation.

This article will discuss this initiative and will specifically focus on the ways in which this programme aims to connect upstream genomics research to its downstream development objectives of helping resource poor farmers in drought-prone areas. For this reason, the first half of the article will introduce and discuss the setup of the programme itself and its research agenda. From this discussion, two elements emerge that are crucial in the programme's ambition to link upstream genomics research with downstream agricultural development. The first is the setting of priorities by the programme on an upstream level, in order to develop technologies that will actually address problems that farmers encounter. The second element is the building of an innovation chain that connects upstream genomics research with downstream variety development and testing. While that is an interesting challenge in itself, this article aims to take the discussion beyond the notion that strong institutional linkages are crucial in an effective innovation chain. For that reason, the second half of the article will adopt an innovation systems perspective and will explore the potential for a more dynamic perspective of how upstream genomics research and downstream innovation systems can be complementary, and what kind of technologies allow for their linkage. As will be shown, this results in an interesting novel function of genetic technologies when they are embedded in a service-like approach, rather than presented as solutions to agricultural production problems as such.

THE GENERATION CHALLENGE PROGRAMME –UPSTREAM GENOMICS RESEARCH FOR PRO-POOR AGRICULTURAL INNOVATION

The Generation Challenge Programme is one of the four 'Challenge Programmes' of the Consultative Group on International Agricultural Research (CGIAR). The CGIAR is a group of 15 international agricultural research centres worldwide that focus on the improvement of genetic resources for agriculture in developing countries. These research centres are diverse in their setup; while some centres focus on a set of the 22 CGIAR mandate crops, others focus on specific agro-climatic regions or policy issues.[3] According to the CGIAR website: *"A CGIAR Challenge Program (CP) is a time-bound, independently-governed program of high-impact research, that targets the CGIAR goals in relation to complex issues of overwhelming global and/or regional significance, and requires partnerships among a wide range of institutions in order to deliver its products."*[4] The Challenge Programmes are an institutional novelty within the CGIAR system, in the sense that they are not restricted to a single research centre, but function in between and 'above' the various agricultural research centres. The current four Challenge Programmes focus on 'tapping into crop diversity to improve drought tolerance' (Generation CP), nutritional quality (HarvestPlus), managing food production and water scarcity (Water & Food), and reviving agriculture in Sub-Saharan Africa (Sub-Saharan Africa CP).

The Generation Challenge Programme is committed to the use of comparative genomics, marker assisted breeding, and genotyping technologies to empower plant breeding for resource poor farmers. The underlying rationale is that these kinds of modern genetic technologies are increasingly being used in plant breeding in developed countries, and provide powerful ways of advancing plant breeding, but are difficult to access and use by breeders in developing countries (Ribaut et al. 2008). So far, investments in genomic maps of agricultural crops have mainly been limited to a few model crops, or crops of commercial interest to developed countries, while many crops of significance for developing world agriculture have remained 'orphan crops' in terms of research investments (Naylor et al. 2005). Moreover, intellectual property restrictions on newly developed technology and biological material often restricts the use of these innovations for agricultural development in 'the South' (Atkinson et al. 2003; Louwaars 2007; Louwaars et al. 2008). The CGIAR as a whole is committed to use plant breeding technologies for crops of relevance to developing world agriculture, however its funds are limited and the focus of many CGIAR institutes on specific mandate crops means that potential synergies made possible by comparative genomics have not materialized so far. The Generation Challenge Programme is specifically intended as a cross-cutting initiative to bring together cutting edge genomics research from different institutes, to take advantage of comparative genomics for gene discovery, to build an 'integrated platform of molecular biology and bioinformatics tools', and to facilitate the delivery chain from upstream genomics research to actual innovations in farmers fields (Bruskiewich et al. 2006; Generation Challenge

[3] See www.cgiar.org for a list of the various CGIAR institutes, their primary focus, and a list of the 22 CGIAR mandate crops (last accessed 17 September 2008).
[4] See http://www.cgiar.org/impact/challenge/index.html (last accessed 17 September 2008).

Programme 2007).

The GCP is organized in 5 subprogrammes, which focus on different activities, ranging from exploring existing genetic diversity and trait discovery, to developing bioinformatics tools and capacity building (see Box 1). Research in each of these subprogrammes is divided in *competitive projects* which have an innovative character, and *commissioned projects* which are more specifically aimed at addressing bottlenecks in the innovation chain, and in making sure that products from earlier research can be validated and taken up into downstream breeding programmes. In addition, GCP makes a distinction between *horizontal* and *vertical* projects, in which the horizontal projects are broad in scope and provide wide platforms of knowledge and methodologies. Making genomic maps of CGIAR mandate crops is such a horizontal activity. The vertical projects in contrast have a much more narrow focus on a specific crop and region, and range from upstream activities down to concrete product development. The scope of these projects is limited since they engage with the difficulties and peculiarities of individual farming systems, but their impact can be significant if successful. The hope is that a number of successful examples of vertical projects will provide a proof of concept, a legitimation of the GCP approach, and a starting point for scaling up by other programmes or donors.

Box 1: Subprogrammes of the Generation Challenge Programme

1. Genetic diversity of global genetic resources
2. Genomics towards gene discovery
3. Trait capture for crop improvement
4. Genetic resources, genomics and crop information systems
5. Capacity building and enabling delivery

DELIVERY PLANS, PRODUCTS AND USERS

For the Generation Challenge Programme, one of the main challenges is to make sure that the upstream genomics research actually leads to improved breeding programmes and crop varieties with new traits. This has materialized in a strategy to write a delivery plan for every project that is being funded by GCP (above a funding threshold of $200,000), identifying the concrete 'products' of the research –whether they are genes, markers, germplasm or methodologies- and to identify primary and secondary users of these products. The GCP and its projects are clearly focused on doing upstream research, and therefore cannot engage in the concrete variety development downstream. However, the programme does aim to have an oversight role in making sure that its products cán be taken up downstream, are taken up, and will actually lead to useful innovations for resource poor farmers. In practice, project leaders are required to interact from an early stage onwards with downstream research partners, which are commonly scientists working at national research institutes of developing countries. By involving these people, the outputs of the project are thought to be better tailored to the needs of the downstream partner, increasing chances of a successful innovation process. In addition, next to tailoring research projects to the needs of downstream partners, the building of capacity of these downstream partners is a focal point, in order to ensure that they can actually take up the genetic information or technologies that are being produced by GCP. Both the development of delivery plans, and organizing capacity building of downstream partners are important objectives of subprogramme 5 (SP5).

This focus on delivery and capacity building at national research partners demonstrates how GCP operationalizes its commitment to having an impact. In doing so, the GCP cannot possibly control and organize all steps in the innovation process going from upstream gene discovery to varietal development in a specific context. In spite of that restriction, the facilitating role of the programme and its oversight role are meant to create favourable conditions for the development of actual innovations in terms of new crop varieties for resource poor farmers. This output oriented character of the programme and the explicit focus on identifying products and different levels of users for every project is an important characteristic of GCP. It is typical for contemporary debates on the effectiveness of public sector agricultural research, on 'innovation systems' for agricultural development, and fits in with ideas to stimulate interaction between different institutes and actors in order to bridge the gap between invention and innovation. But, next to making sure that bottlenecks in the innovation chain are being addressed, the question emerges what kind of farmers GCP actually targets, and with what kind of strategy for agricultural development. In other words, we need to shift focus from the *procedure* of delivery, to the *target(s)* and *objectives* of delivery.

TARGETING THE POOR - FARMING SYSTEMS, CROPS AND TRAITS

Like any research programme, the GCP is caught in between ambitious goals and a limited amount of funding and lifetime. This has led the programme to execute a priority setting exercise in order to define a coherent set of principles for the selection of projects to be funded by GCP. Since priority setting exercises force a programme to limit its activities and potential beneficiaries, they expose how formal priorities are operationalized in practice, in the selection of projects. The GCP priority setting exercise and its outcomes are elaborated below, and their impact on targeting resource poor farmers are discussed.

In terms of discussing how the outcomes of GCP can reach resource poor farmers specifically, the focus of the programme on drought tolerance is a first important element. Drought as focus trait has been a leading principle right from the beginning of the programme for a variety of reasons. One is the global importance of drought stress on agricultural production (Moffat 2002; Ribaut 2006; Tuberosa and Salvi 2006), and hence the potential to have a great impact if drought resistance can be successfully managed. Moreover, considering that the GCP would not focus on a single crop, or small set of crops, a trait was chosen that is problematic across a wide range of crops. Thirdly, drought tolerance is a trait that is very difficult to tackle because of it's complexity. In interviews, some scientists jokingly refer to it as the 'holy grail' of plant breeding for the developing world. The supposed value of comparative genomics and high-throughput analyses for pro-poor plant breeding would be best demonstrated by addressing a trait that has been notoriously difficult to crack in the past. Drought tolerance is just such a trait.

In practice, the focus on drought includes a number of drought related traits such as aluminium toxicity, phosphorous uptake and in some cases completely different traits that turn out to be main limiting factors for production. For example, in some cases drought is an important limiting factor for production, but improved drought resistance only provides added value if a certain disease or pest is addressed as well. This can be a reason for specific GCP projects to widen their focus on different traits, especially in the downstream variety development.[5] Moreover, it is important to note that drought as such is a very complex trait, which is manifest through very different mechanisms. In practice this means that research is focused on different genetic mechanisms which are of relevance in different drought prone environments, for example depending on the moment of drought stress early or late in the growing season.

With drought tolerance as priority trait, the priority setting exercise conducted by GCP needed to identify areas where the need for improved food production was highest, where drought was indeed a serious limiting factor, and where there was a scope for improvement through the release of improved seed varieties. Only in that context would the work of GCP have a significant added value. A farming systems approach has been taken as starting point for identifying what reasonable target areas could be. In 2001, a team led by John Dixon developed a list of farming systems related to poverty in six main developing regions (Dixon et al. 2001).[6] Two types of criteria were used to identify these farming systems: first the available natural resource base, climate, typography, farm size and tenure; secondly, household livelihood patterns, technologies and farm management and organization. These criteria led to a list of 72 distinct farming systems, with an average agricultural population of about 40 million (FAO 2001). Together, they form a global map of agricultural production in the developing world that cuts across national boundaries and provide a novel view on their constraints and potentialities.

GCP has chosen to take these farming systems as heuristic for identifying problem

[5] A concrete example is a project on cassava, in which new genetic variation from Colombia is brought to Africa in order to address drought tolerance. However, in validating the material in Nigeria, virus infestation appeared to be a major limiting factor, not only to production, but also to the breeding programme itself. Although the primary focus of the GCP project is on drought tolerance, the same genetic tools and knowledge can be used to start selecting for virus resistance as well.

[6] These six regions are: Sub-Saharan Africa, Middle-East and North Africa, Eastern Europe and Central Asia, South Asia, East Asia and Pacific, Latin America and Caribbean

regions, and selected for the farming systems in which chronic poverty was apparent, and drought a major limiting factor for production (Generation Challenge Programme 2006). As poverty indicator, the number of children that are stunted in their growth (poor growth in length for age) had been chosen, since this indicates malnourishment over a prolonged period in time. A number of 2.5 million stunted children per farming system was set as threshold. In order to select for drought stress in a farming system, a failed season drought model was developed, indicating what areas would be most prone to drought stress in agricultural cultivation. The overlaying of these data on the map of global farming systems led to a selection of priority farming systems in which chronic poverty was a major issue and drought a major limiting factor for agricultural production. After leaving out a number of farming systems based on trees or pastoralism (farmers with livestock) for which different mechanisms of poverty are thought to play a role, a set of *15 target farming systems* remained. In order to determine whether crop research could indeed be an appropriate response to the problems in these target farming systems, the productivity of the major crops in these systems was assessed in order to verify that the chronic malnourishment that was identified indeed corresponded to poor agricultural production (Hyman et al. 2008). Since this was the case, it was concluded that genetic improvement could potentially help to increase food production and hence alleviate poverty. Next to identifying 15 target farming systems, a number of *13 priority crops* were identified that represent 95% of the cultivated area in those farming systems.[7] See Table 1 for an overview of the priority farming systems for the GCP and their main crops.

15 Target farming systems, 13 priority crops and one priority trait: that is the main result of the priority setting exercise as conducted by the Generation Challenge Programme. The list of target farming systems and their major crops provides a concrete narrowing down of the research focus for the Generation Challenge Programme. It helps to concentrate the GCP funds on a limited number of crops, and prevents a dilution of funds and a loss of impact of the research. But what do these priorities mean in terms of research agenda, and the addressing of needs of the resource poor?

[7] These 13 crops are: barley, beans, cassava, groundnut, maize, millet, potato, pulses (specifically cowpea and chickpea), rice, sorghum, sweet potato, and wheat (Hyman et al. 2008).

Region	Farming system	Crops in farming system
South Asia	Rice-wheat	Rice, pulses, (chickpea), millet, wheat, maize, bean
South Asia	Rainfed mixed	Rice, millet, sorghum, chickpea, bean, groundnut, maize, wheat
East-Asia and the Pacific	Upland intensive mixed	Maize, rice, wheat, sweet potato, potato, bean
East-Asia and the Pacific	Lowland rice	Rice, maize, wheat, sweet potato, groundnut
South Asia	Rice	Rice, pulses (chickpea)
Sub-Saharan Africa	Cereal-root	Sorghum, millet, pulses (cowpea), maize, groundnut, cassava
Sub-Saharan Africa	Maize mixed	Maize, cassava, sorghum, pulses, groundnut, millet, bean, sweet potato
South Asia	Highland mix	Rice, maize, wheat, potato, groundnut, pulses (chickpea)
Sub-Saharan Africa	Root crop	Maize, cassava, rice, sweet potato, cowpea, sorghum, groundnut, bean
South Asia	Dry rainfed	Sorghum, millet, chickpea, groundnut, bean
Sub-Saharan Africa	Agropastoral millet/sorghum	Millet, sorghum, pulses, groundnut, maize
Latin- America and the Caribbean	Maize-beans	Maize, bean, sorghum
Sub-Saharan Africa	Highland temperate mix	Maize, wheat, sorghum, barley, millet pulses
East-Asia and the Pacific	Temperate mixed	Maize, wheat, potato, groundnut, millet
East-Asia and the Pacific	Highland extensive mixed	Rice, maize, wheat, potato, groundnut, pulses

Table 1: Priority farming systems for the Generation Challenge Programme (*source: Hyman, G., S. Fujisaka, et al. (2008). 'Strategic approaches to targeting technology generation: Assessing the coincidence of poverty and drought-prone crop production.' Agricultural Systems, 98(1): 50-61).* Regions are listed in order of highest to lowest absolute number of stunted children per farming system. For each farming system, the main crops are given.

CHALLENGES FOR A SCIENCE-LED RESEARCH PROGRAMME

The aim of the Generation Challenge Programme is that its upstream genomics research into mechanisms of drought tolerance leads to outputs that are ultimately relevant for resource poor farmers in drought prone areas. The priority setting exercise as elaborated above has provided the programme with a legitimation for focusing on drought, and has indicated in what farming systems and crops this research is most likely to have an impact. In fact, this priority setting exercise is a very explicit way of technically defining what would constitute an appropriate technical output of the GCP. What is remarkable in that respect is that the operationalization of appropriateness has taken place in relative isolation of a concrete farming system, and the problems that farmers encounter in real life. Clearly, there is a wide legitimacy for addressing drought tolerance, but it seems fair to conclude that the research agenda is primarily science-led. This raises the question to what extent such a technical and science-led operationalization of appropriateness is legitimized in order to produce useful technologies for resource poor farmers, and to what extent it represents a specific perspective on how agro-technological development should be organized.

In this respect, a first observation that can be made is that the legitimacy of a top-down science driven approach to a certain extent depends on the kind of trait the programme is working on. For some traits – or technical solutions in general – a very precise and locally specific understanding of the problem is essential for successfully solving it. Disease or pest resistance is such a trait, which strongly depends on local climatic conditions, crop ecology and local strains of viruses. The way this applies to drought tolerance as a trait depends much on the understanding of this trait. As mentioned before, drought tolerance in general is a trait that can be useful for many farmers, regardless of their precise circumstances or cropping system. However, taking a closer look at the trait reveals its complexity, its frequent co-occurrence with other problems with soil fertility or toxicity, and with the vulnerability of crops to pest infestation. This means that in practice, a very local understanding of the production constraints will probably be needed to successfully develop new crop varieties that can deal with the specific circumstances on a higher level of detail.

Having said that, it is possible that a limited number of genetic mechanisms in fact determines drought tolerance across a wide range of crops and circumstances. For example, the ability of a crop to *perceive* drought and to adapt its metabolism accordingly may be regulated by a very specific genetic switch, in a wide range of plants. The discovery of such a mechanism would mean that basic genetic research can have a great influence on the development of drought tolerant crops, in spite of the different manifestations of drought stress/tolerance in different environments. In that sense, the success of a generally science driven approach to address a trait like drought tolerance will depend on the genetic mechanisms that play a role, which in turn means that it is an empirical question which will only become clearer during the research of GCP itself.

However, next to the technical variation in what drought stress means, there may be completely different factors at play that limit agricultural cultivation, and that remain opaque in a merely technical view on what appropriate technology is. For example, while a specific farming system may be characterised as 'drought prone', that does not mean that providing drought tolerant varieties is the most apt way of addressing poor agricultural performance. In fact, actual problems in cultivation may have less to do with the poor quality of the varieties being grown, than with political decisions on land use within a country. Take for example the 'maize-beans farming system', which is the only target farming system of the GCP in the Americas. If this farming system is diagnosed with sub-average production levels, genetic improvement of maize or beans may clearly be one potential solution.

However, in many Central American countries, an unequal division of fertile lands is a well known and historical problem since the colonisation of the continent (Morley 2001). If the most fertile lands are in the hand of a small rich elite, and to an important extent dedicated to export crops such as coffee or fruit, the reason that many other farmers have sub-optimal yields may as much be related to the division of fertile land, as to the quality of their germplasm (Garst and Barry 1990). Clearly, such locally diverging, socio-political dimensions of problems in agricultural production are not taken on board in the research priorities of the GCP.

The argument that arises is that a priority setting exercise based upon statistics of chronic undernutrition and models of drought stress on agriculture may provide a legitimation for focusing on drought tolerance in certain crops for certain regions, but that a more localized understanding of the problems and potential solutions may be required to really contribute something useful for agricultural cultivation. This creates some tension between a general focus on upstream genomics research to drought tolerance, and the diversity in local manifestations of the problem at hand. How the Generation Challenge Programme addresses this tension will be discussed in the upcoming sections.

A final challenge that arises is related to actually reaching the resource poor farmers that are targeted by the research programme. Arguing that specific genetic technologies can have an impact in farmers' fields is not the same as arguing that the impact is especially relevant in the context of poverty alleviation. Andy Hall et al. concretely describe a concrete manifestation of this problem in a project on the improvement of post-harvest conservation of mangos (Hall et al. 2003; Hall et al. 2004a). In this project, technical assistance was intended to benefit resource poor mango farmers, but Hall et al. report that in practice the innovation process was dominated by large-scale, non poor mango producers who were most actively involved in mango export. By failing to investigate stakeholder agendas at an early stage of the project, not only innovation itself was impeded because of institutional constraints, but – at least as important – the chance that anything coming out of the project would actually benefit resource poor mango farmers was very low.

Obviously, the kind of downstream research partners that GCP works with matters enormously in order to make sure that products do not only reach farmers' fields, but to make sure that they also actually contribute to poverty alleviation among small scale farmers. Concretely, this requires GCP to go further than making sure that downstream partners are able to take up the outputs of upstream genomics research and translate them into new crop varieties. Instead, it requires the programme to very consciously evaluate who the farmers are that are targeted by the downstream research partners, and are therefore most likely to benefit from the GCP products.

Note that the appropriateness of technological development here no longer primarily depends on the material design of the drought resistance technology. In fact, in spite of the claim that drought tolerance as trait is essentially of most relevance for resource poor farmers in drought-prone areas, it might as well as unlock new arid areas for industrialized farming that would not have been remunerative for cultivation without better drought resistant crops. In other words, while in a concrete context of application the precise material design of new crop varieties can be expected to be of relevance, on the more upstream level at which GCP works, it is of crucial importance to embed the technology in an institutional setting that ensures its appropriateness for resource poor farmers, rather than relying on the trait's relevance for resource poor farmers alone.

COMPLEMENTARY INNOVATION SYSTEMS

In discussing the challenges for GCP to contribute to agricultural development for resource poor farmers, the issues that emerge are in fact directly related to the tension between bottom-up versus top-down innovation trajectories. While a bottom-up technology development project may be closely in touch with local needs and circumstances, it is unlikely to engage in comparative genomics research and to harness its potential to find new genetic mechanisms of dealing with drought stress. It takes a significant amount of upstream scientific work to actually be able to unlock this 'genetic potential' which is thought to be present in existing germplasm collections. On the other hand, a science led activity will always have difficulties in dealing with the peculiarities and complexities of different farmers 'on the ground'. It may provide generally applicable solutions, but their adaptation to different local situations is quite another challenge, which is generally taken up by local research institutes, extension services or development projects. But does that mean that science-led innovation in new crop varieties is inherently less appropriate than bottom up innovation processes?

Rather than continuing the top-down versus bottom-up dichotomy with its apparent contradictions, it seems more appropriate to explore the complementarities between both approaches, like advocated by the Systems of Innovation framework. This conceptual framework has recently been adopted by a number of scholars as a new perspective on the question of how to organize biotechnology development for resource poor farmers. The framework goes back to the conceptualization of 'National Systems of Innovation', as originally developed by authors like Freeman, Nelson and Lundvall (Freeman 1987; Lundvall 1992; Nelson 1993), somewhat more recently reviewed by Charles Edquist (Edquist 1997), and summarized in relation to development issues by Andy Hall (Hall and Yoganand 2004; Hall et al. 2004b; Hall 2005).

According to Hall the concept of National Systems of Innovation emerged because conventional economic models had limited power to explain innovation, which was viewed conventionally as a linear process driven by research. In contrast, the innovation systems framework sees innovation in a more systemic, interactive and evolutionary way, whereby networks of organizations, together with the institutions and policies that affect their innovative behavior and performance, bring new products and processes into economic and social use (Hall 2005). The framework has become rather popular during the last decade and is frequently used to understand and strengthen innovation at national, regional and sectoral levels.

The conceptual framework of systems of innovation consists of a wide, but somewhat diffuse body of literature with various approaches. In addition, these approaches have changed over the last few decades (Smits and Kuhlman 2004). In Box 2, some key points are summarized that characterize contemporary thinking about Systems of Innovation.

Box 2: Key elements of the Systems of Innovation framework

- The Systems of Innovation framework has a focus on innovation processes, rather than on mere production of knowledge.
- The framework conceptualizes research as part of the wider process of innovation, and therefore helps in identifying the scope of the actors involved and the wider set of relationships in which research is embedded.
- It breaks out of the dichotomy between technology-push and demand-pull theories. Instead, it recognizes that both processes are potentially important at different stages in the innovation process.
- It recognizes that the institutional context of the organizations involved promotes dominant interests and shapes the outcomes of the innovation system as a whole. It therefore urges to examine and reveal which agendas are being promoted, and highlights the arena in which the voice of the poor can be promoted.
- It recognizes a system of innovation as a social system, and therefore does not just focus on the degree of connectivity between different elements, but on learning and adaptive processes.
- It is a framework for analysis and planning, and not restricted to a single disciplinary convention.

Source: Hall, A. and B. Yoganand (2004). 'New institutional arrangements in agricultural research and development in Africa: concepts and case studies'. In: Innovations in Innovation: reflections on partnership, institutions and learning. A. Hall, B. Yoganand, R. V. Sulaiman et al, Eds. Patancheru, New Delhi: CPHP, ICRISAT, NCAP.

The Systems of Innovation framework provides a helpful tool to conceptualize the innovation process and the role of different institutions and activities as part of the larger innovation system. However, it does not provide a single model of how innovation should be organized. For example, Andy Hall has concretely explored the importance of agricultural innovation systems, and has indicated both their diversity and complementarities. Rather than formulating the ideal type agricultural innovation system, he elaborates a genealogy of different types of innovation systems in international agricultural development (Hall 2005). This genealogy ranges from highly science driven public sector research, via R&D led agribusinesses, to pro-poor participatory innovation for complex agro-ecologies.

More important than the exact typology of agricultural innovation systems, he argues that the recognition of diversity in innovation systems is important for a number of reasons:

> *"Firstly, it allows policy and capacity development activities to recognize and support the co-existence of different types of innovation capacity. This helps break out of the false dichotomy whereby old practices are vilified at the expense of new without recognizing synergy. Secondly, it allows emphasis to be given to ways of strengthening the strategic, purpose-oriented interaction of these systems at various points of intersection. This shifts attention to complementing and integrating different ways of producing and using knowledge rather than arguing for homogeny and, for example, insisting that all approaches having to become participatory or partnership based or that all approaches have to be science-led. Clearly neither of these propositions is workable and could undermine well intentioned capacity development efforts."* (Hall 2005, pp. 627-628)

Hall stresses the complementarity of different innovation systems and the roles that different institutes can play. But at the same time, he acknowledges that a challenge still lies ahead in actually linking different types of innovation systems and for example bringing biotechnology innovation systems to bear on farmer participatory innovation systems. This is exactly the challenge for GCP in linking up with different downstream research partners. A potential complementarity may be observed between the upstream research that GCP funds, and the engagement with the complexity of farmers on the ground that farmer participatory innovation systems are best at, and which is more typical for GCP's vertical research projects. But the question is how this complementarity can be best exploited in practice, and whether an innovation chain in which upstream outputs are transformed into a series of downstream inputs is the most useful heuristic. Considering the interest in locally contextualized agro-technology development (as expressed in the introduction of this article), it may be worthwhile to consider how GCP outputs can be valuable in a range of downstream development trajectories, and what would constitute an effective technical interface between upstream genetic resources and downstream applications.

COMPLEMENTARITY IN PRACTICE: DIFFERENT RESEARCH PARTNERS AND TECHNOLOGY AS A SERVICE

The first attempt of the Generation Challenge Programme to exploit the complementarity in science-driven and bottom-up innovation processes is by strategically investing in the aforementioned horizontal and vertical research projects. While horizontal research is more upstream and focused on the general understanding of genetic mechanisms behind drought tolerance, vertical research projects are committed to the delivery of concrete new crop varieties, adapted to the specific problems of farmers in a specific region. These vertical research projects are also responding to prioritized needs of farmers, beyond the focus on drought tolerance, and hence they are argued to be more demand driven than horizontal research projects. Because of their more downstream and focused nature, they do have to take into account what the concrete manifestation of drought stress is on a local level, and how problems of agricultural production are often a combination of a wider set of factors. Whether this is a successful approach in practice depends on the evaluation of the specific vertical research projects. However, in terms of linking upstream research with downstream variety development, this approach demonstrates the possibility to combine different innovative dynamics within the same programme, ideally leading to an optimal integration of perspectives and interaction between different levels of innovative activity.

In addition, as becomes clear out of an inventory of its projects, the GCP is capable of linking up with a wide range of downstream research partners, with different technical needs and objectives. The most obvious downstream research partners for the Generation Challenge Programme are the national agricultural research institutes in any developing country. These are the kind of institutes that have been beneficiaries of CGIAR related research for decades, and which generally play a central role in the agricultural policies and research of developing nations. However, in practice, the range of partners appears to be wider than just these national research institutes. A nice case in point is the project on common bean (*Phaseolus vulgaris L*), which is focused on the Maize-Beans target farming system in Central America, and focuses on drought stress and diseases that occur under drought and low soil fertility conditions. The project is headed by a scientist from INIFAP[8], the Mexican national agricultural research institute, but has partners in Mexico, Nicaragua, Cuba and Haiti. What makes this project relevant for the discussion in this article is that the partners from the countries involved, are very different in character. While the development of varieties and dissemination of seed in Mexico will be carried out with an organization of bean producers, the partner in Cuba is the national research institute that will use the GCP outputs for participatory breeding with Cuban farmers. In Haiti, little public investments are made in agricultural research and extension, and a national agricultural research centre is lacking. Therefore, contact has been made with an NGO ('ORE') that will be engaged with the dissemination and evaluation of new bean varieties that will be produced as part of the GCP project.

These completely different downstream organizations demonstrate a certain flexibility of the GCP in terms of linking up with different research partners. This variety in downstream research partners and their approaches to agricultural development demonstrate that the upstream GCP research does not preclude a diversity in its operationalization on a downstream level and that it does not put a major restriction on the kind of collaborations that are set up. In addition, the diversity in downstream research partners illustrates that rather than an innovation chain, an innovation network may be a more appropriate heuristic to map and represent the interactions between the upstream GCP innovation system and a range of different downstream innovation systems.

[8] INIFAP = *Instituto Nacional de Investigaciones Forestales, Agrícolas y Pecuarias*

TECHNOLOGY AS A SERVICE – THE GENOTYPING SUPPORT SERVICE

The complementarity between horizontal and vertical research projects, and the collaboration with different types of downstream research partners may indicate an institutional flexibility. However, in practice it does introduce new technical requirements for the outputs of GCP. This is for example visible in the differences between the participatory breeding programme in Cuba, and the NGO in Haiti that does not have the capacities to get involved in breeding, but will focus on dissemination of improved seeds. For the GCP project, this means that outputs will have to be attuned to different needs; concretely that a wider breeding population with some diversity will have to be provided for the participatory breeding exercise in Cuba, while a limited set of finished varieties can be disseminated in Haiti. However, the question of what kind of technical interface would support a meaningful complementarity between science-led and bottom-up innovation has a wider relevance.

The GCP produces a wide range of 'technical' outputs, which include knowledge about genes, traits, molecular markers to introgress such genes, and potentially parental material containing new traits (like drought resistance) to be incorporated in breeding programmes. In addition, GCP creates communities of scientists working on the same crop, technology platforms and genomic maps of crops that are of wider use and significance. These outputs may be useful in wide range of settings, but they do require a certain level of expertise to be taken up in further downstream research or variety development. The most straightforward way of dealing with this problem is to invest in downstream capacity building, which is the main focus of subprogramme 5. The activities of this subprogramme include the setup of training courses, exchange programmes of scientists, and other capacity building activities that are primarily aimed at increasing the level of up-to-date knowledge about genetics, the interpretation of genetic data and the use of molecular markers in breeding programmes.

In addition, a more structural problem has been identified with the use of molecular markers and other genetic analyses because of the lack of basic infrastructure with many research partners in the south. Access to electricity, clean water, personnel for technical assistance, and reagents may be structurally difficult, and not easy to overcome by a couple of capacity building exercises, or investments from the GCP.[9] For this reason, a Genotyping Support Service (GSS) has been set up that allows the outsourcing of genetic analyses to specialized institutes in developed countries at competitive prices. The GSS plays an intermediate role in helping research partners to develop research proposals, in linking with specialized genotyping institutes, and in interpreting the data that come out of the exercise. While the exact genotyping activity can be tailored to the needs of the research partner, in general two kinds of major categories are distinguished in the proposals for the GSS: (1) determining the genetic diversity in

[9] See also similar experiences of the Convergence of Sciences project, as reported in (Richards et al. 2009).

breeding material or germplasm bank accessions, and (2) running marker assisted selection in a population on a trait for which markers are available.

Although the Genotyping Support Service can be seen as a way to overcome bottlenecks in using the other outputs of the GCP (like molecular markers for drought), it also allows for completely different uses, and interesting synergies between different projects. Take the example of groundnut research at three different partners of GCP in Brazil, Bolivia and Senegal. Groundnut (*Arachis hypogaea L.*) is the most widely cultivated legume in Africa, with most of the production originating from drought-prone areas. Drought considerably reduces yield and production. Cultivated groundnut has a narrow genetic basis and the first step for improving drought tolerance in this crop is by enhancing genetic diversity. GCP is involved in a project in Senegal, one of the main groundnut producers in West Africa, aimed at evaluating new sources of drought resistance in groundnut. The Brazilian agricultural research institute EMBRAPA[10] had earlier been involved in projects aimed at widening the genetic base of Brazilian groundnut production, and had been successful in making some distant crosses between cultivated varieties and wild varieties of groundnut. Meanwhile, in Bolivia – the centre of origin of groundnut and still home to a wide diversity of the crop – PROINPA[11] is involved in mapping and conserving groundnut diversity. Like in many countries, the diversity in traditional landraces has come under pressure with the introduction of improved varieties from developed countries. PROINPA has a mandate from the Bolivian government to be a curator for certain germplasm collections, and as such is concerned with maintenance of existing crop diversity. In addition, the foundation is interested in breeding with traditional landraces in order to provide Bolivian groundnut farmers with varieties that both have good agricultural characteristics, and fit the needs of Bolivian consumers.

A problem for PROINPA is the collection and categorization of their collection of groundnut germplasm, which makes its valorisation for future breeding activities more difficult. Conventionally, phenotypical (morphological) characteristics were used to categorize accessions of the seed bank. However, since the appearance of groundnuts (and other crops) can be strongly influenced by environmental conditions, this is a rather inefficient and unreliable way of mapping diversity. In order to get a better idea of the real genetic diversity that is present in the Bolivian groundnut collection, a proposal was submitted for the Genotyping Support Service in order to fingerprint the collection, and to map the diversity that is present. This resulted in a set of genetic information that provided a much more precise image of the diversity within the collection, and its position vis-à-vis other groundnut collections. Moreover, it became clear that the Bolivian collection contains a number of accessions that are unknown to other seed banks of groundnut, and are therefore potentially valuable sources of new traits.

For PROINPA in Bolivia, this exercise was about getting a better idea of the diversity that is present, in order to make better use of it in future breeding

[10] EMBRAPA = *Empresa Brasileira de Pesquisa Agropecuária*
[11] PROINPA = *Promoción y Investigación de Productos Andinos*

programmes. However, obvious synergies emerge with the work of EMBRAPA in Brazil and the GCP project on groundnut in Senegal. While EMBRAPA has experience with actually widening the genetic base of groundnut through crosses with wild relatives, the additional genetic diversity that can be created this way may be very valuable for the project in Senegal. What this demonstrates is that the combination of gene discovery, marker development, marker assisted breeding and genotyping technology can be used in very diverse context, with different objectives.

In addition, a fruitful link between the Genotyping Support Service and 'pro-poor participatory innovation for complex agro-ecologies' can be indicated. Already, research partners are not required to be able to extract DNA from their germplasm collection: instead, providing tissue material from plants to be screened is sufficient for the specialized genotyping lab to extract DNA and to perform the analysis. If this kind of service is not only provided by GCP but becomes an integrated service of many national research institutes, it is only a small step to offer local and small scale participatory breeding programmes to provide marker assisted selection, *in addition to* the participatory selection with farmers. The value of such a service would lie in the selection for traits that are difficult to assess by farmers, because they are not visible to the eye. Examples include the processing quality of potatoes, which depends on the sugar content of potatoes, or horizontal disease resistance which depends on the presence of a number of quantitative genetic elements. For farmers it is nearly impossible to assess the difference between strong vertical resistance that easily breaks down, and somewhat weaker horizontal resistance that is expected to be much more durable.

If selection on such difficult traits by markers is *complemented* by a participatory breeding programme in which farmers themselves can identify what kind of new varieties would suit their production best, we can speak of a truly successful linkage between the complementary capacities of molecular scientists and farmers. The effects of such an approach would go beyond making breeding more efficient. In terms of social relations of innovations, it implies that genetic approaches to breeding do not require an externalization of the breeding and selection process, but rather that the genetic perspective becomes an integrated part of an innovation process that is essentially led by farmers themselves, as part of a participatory breeding programme.

DISCUSSION – THE POTENTIAL FOR A SERVICE-LIKE APPROACH TO AGRO-TECHNOLOGICAL INNOVATION

This article was motivated by an interest in the potential of upstream genomics and biotechnology research for agricultural development. Pleas for a contextualized and 'appropriate' agro-technology development strongly focus on the importance of bottom-up innovation processes, stakeholder involvement and local development. The question was raised whether this would inherently disqualify any upstream scientific research programmes to contribute to agricultural development and poverty alleviation, or whether such programmes can in fact have a meaningful contribution to contextualized, endogenous agricultural development.

In discussing the case of the Generation Challenge Programme and the relationship between its upstream research and potential downstream applications, an important argument has been borrowed from Andy Hall to move beyond a dichotomy between top-down and bottom-up innovation dynamics, and to look at the complementarity of these approaches instead (Hall 2005). In exploring this complementarity in the context of the GCP, it becomes apparent that the kind of technologies and knowledge that GCP produces are to an important extent enabling technologies, or tools in further research. Rather than creating concrete artefacts that farmers can use in their production, the production of genomics maps, knowledge about genetic mechanisms, or in a later stage molecular markers allow downstream research partners to advance their breeding programmes on a local basis. This means that rather than providing 'prefabricated solutions' for agricultural problems, the GCP provides a pool of upstream genomics knowledge, capacity and research tools to allow different types of downstream research partners to develop their own solutions. The most convincing and extreme example of this approach is the Genotyping Support Service, which very explicitly does not provide an agricultural product, but a *service* that can be plugged into different types of research programmes, depending on local needs.

As such, the GSS in particular demonstrates how upstream genomics knowledge can be made accessible upon demand, and cannot replace essential parts of bottom up participatory work, but can be an important complementary element in developing relevant new crop varieties for resource poor farmers. This also creates a situation in which bottom-up and top-down innovation systems are not conflicting or contradictory, but potentially strongly complementary. The availability of a pool of genomics information and genotyping facilities would then create an interface between upstream genomics information and local participatory innovation systems that allows its use in a locally defined and tailored way.

Note that this understanding of the complementarity of different innovation dynamics also has implications for the debate on stakeholder involvement in (agro-bio)technology development. The article starts by expressing an interest in developing technology in a contextualized way, which generally leads to an argument for bottom-up processes and participatory approaches. However, the article does not extend that argument to upstream phases of genomics research, as done by the Generation Challenge Programme. In fact, there seems to be little room for the practical and meaningful involvement of farmers on the level of upstream genomics research. Rather than finding ways to involve or represent farmers at this upstream stage in research, it may be more fruitful to acknowledge and exploit the complementarities between upstream science-led research programmes and downstream bottom-up initiatives. This shifts attention from direct stakeholder involvement on all levels, to the institutional configurations and technical outputs that can support such complementarity. In other words, rather than finding ways to meaningfully involve farmers in upstream genomics research, the goal should be to increase the accessibility of research outputs and to stimulate the flexibility in their downstream application local development initiatives.

It is important to stress that a service-like approach as described here in reference to the Generation Challenge Programme, or the Genotyping Support Service does not in itself solve all dilemmas regarding the local adaptation of agro-technological innovation. As mentioned before, the downstream research partners that the GCP collaborates with are of extreme importance for the further development and application of genetic tools made available by GCP research. The observation has been made that GCP is capable of collaborating with a wide variety of downstream research partners, both in terms of the institutional linkages it creates, as well as in terms of its technological outputs. This at least illustrates the practical complementarity of upstream genetic research with various kinds of local organizations involved in agricultural development. However, as mentioned before in this article, in order to actually contribute to poverty alleviation, GCP is required to go further than making sure that partnerships are made with downstream partners, and that they are able to take up the outputs of upstream genomics research and translate them into new crop varieties. In addition, it requires the programme to very consciously evaluate who the farmers are that are targeted by the downstream research partners, and are therefore most likely to benefit from the GCP products.

For example, CGIAR institutes and programmes (like the Challenge Programmes) commonly work with the institutes of the national agricultural research systems (NARS) in different developing countries. However, these institutes may have different organizational mandates or objectives than those of the CGIAR or GCP. For example, while the GCP aims to contribute to food security among resource poor farmers in developing countries, national research institutes may have a stronger focus on increasing national food productivity or the revenues from agricultural exports. In practice, these objectives can lead to research programmes for relatively large scale farmers, well connected to modern agricultural inputs, in the most favourable regions of a country. In other words, they do not necessarily target the most resource poor farmers of their country, but the farmers with highest return on investment for their research. While this may be fair enough from a national perspective, if this happens it would imply a disconnect from the objectives to focus agricultural development on poverty alleviation. Similarly, even if coherence in institutional mandates and objectives is not the problem, not all downstream research partners may have the affinity or capacity to set up participatory development projects. So, in summary, the institutional objectives and capacities of downstream research partners remain crucial for the final adaptation and application of new crop varieties or genetic technologies.

In spite of such comments and reservations, the Generation Challenge Programme does provide a valuable example of how diversity and multiplicity in innovation trajectories can take shape, based upon the combination of explorative horizontal and focused vertical research projects, the collaboration with a diverse set of downstream research partners, and by using the Genotyping Support Service as technical interface to connect upstream genomics research data to a wide range of bottom-up research projects. This approach does not reduce the importance of a careful selection of downstream research partners. In addition, it may make demonstrating the exact impacts of GCP research more difficult. However, in terms of linking genomics research to development objectives, the networked nature of the Generation Challenge Programme, and the service-like character of the Genotyping Support Service may just be the institutional arrangements that allow upstream genomics science to meaningfully impact upon a multitude of downstream research partners contributing to developing world agriculture.

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