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Participatory Genomics in Quinoa

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Introduction

New technologies are usually developed and applied in the developed countries. Less prosperous countries often do not have the infrastructure and capacity to implement new technologies which results in a minimum benefit. They may attempt to implement new technologies at high costs, but these are often not tailored for their conditions and at the long term may even be deleterious.

This unfavorable situation can be counterbalanced when the implementation of new technologies in these countries is demand-driven and is tailored to the local conditions. We have chosen the combination of the quinoa crop and genomics as a model to describe our quest in which way new technologies in a breeding program can be attuned to the interests of marginal farmers. As genomics has most potential to support breeding programs, we will mainly focus on breeding and genomics, but also take other aspects of the quinoa food network and production chain into account.

The quinoa food production chain in Bolivia

The quinoa crop

Quinoa (*Chenopodium quinoa* Willd.) is a tetraploid cereal that is different from other important cereals, like wheat and barley as these are monocot grasses that show a similar genomics make-up (synteny), while quinoa is a dicot that is not related to these grasses at all. Quinoa belongs to the family of *Chenopodiacae*, with spinach and sugar beet as best-known cultivated member species of this family of over 120 species.

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Quinoa seed has a high content of calcium, phosphorus, iron, fat and protein. The oil content is about 7%, while the starch content is about 60%, with 20% amylose. The average protein content in the grain of about 15% is higher than that in other cereals. In addition, the amino acid composition of the protein is well-balanced and similar in quality to that of casein in milk. These characters make quinoa a very nutritious crop for human and animal consumption.

Quinoa cultivation in Bolivia

Quinoa is a typical crop for the Andes and is mainly grown in altitude between 2500 - 4000 m with an average annual rainfall between 150 - 300 mm. Pests, plant disease and abiotic stresses (especially frost, hail, drought and low soil fertility) are the greatest limits to food production in the high Andes. The crop is highly adapted to diverse climatically conditions and is resistant to frost till -8 ^{o}C at flowering stage and till -2 ^{o}C at milking stage.

The most serious disease affecting quinoa is *Peronospora farinosa* f.sp. *chenopodii* (Fr.) Fr., commonly known as downy mildew (Fleming & Galwey, 1995).

In Bolivia, there are approximately 70,000 farmer families in the Altiplano whereby 55 to 85 % make their living from this crop. Approximately 60 % of the quinoa production is concentrated in the southern Altiplano (Oruro and Potosi), where approximately 15,000 producers are cultivating the variety Quinoa Real. This cultivar is preferred for its large grain size as no other country in the region could produce similar grain quality.

In the last five years, production reached 23,000 metric tons which is cultivated in area over 35,000 ha. The average yield varies between 500 to 650 kg/ha. Both biotic and abiotic factors limit the crop yield. Especially in the southern Altiplano the conditions are so harsh that quinoa is the only crop that is cultivated. As a consequence, farmers' families cannot entirely be dependent on the quinoa production and hence need additional income from other activities.

Quinoa domestication

The centre of origin of quinoa is in the Andean region in South America, where it has been domesticated by the Inca Farmers in the last 5000 years. The Incas used it as main crop, but after the collapse of the Inca Empire, the usage has been diminished. In the last decades, the interest in quinoa production in

Andean countries like Ecuador, Peru and Bolivia has shown a revival, whereby Bolivia became the most important quinoa producer. It is still mainly grown in the Andean region, though also attempts have been made to introduce the crop in Europe (Mastebroek et al., 2002).

Genetic variation and breeding of quinoa

Quinoa is a allotetraploid (2n=4x=36) self-fertilizing species, that probably originates from hybridization of two diploid species and subsequent chromosome doubling. The hermaphroditic flowers easily cause self-fertilization, with 10 to 25% cross pollination in the field. As a result, the quinoa landraces have a high level of heterogeneity and heterozygocity and more advanced cultivars are difficult to keep true to type by farmers who propagate their own seeds. Therefore, new technologies like adequate isolation of the different varieties in the seed production fields should be introduced to the farmers to implement a sustainable way of maintaining and propagating their preferred cultivars. For instance, most of maize farmers select grains for seed increase after harvesting, while, practices such as plot isolation or selection of good plant type is not implemented which can jeopardize breeding efforts (Duijndam .F.P. & C.J. Evenhuis, 2004).The cultivated crop already shows a high level of genetic variation, that allows the selection of adapted cultivars for different ecological conditions and for different markets. This makes breeding relatively simple as selections in landraces can already be quite efficient to improve the crop. Crosses with wild relatives are usually not done and not needed yet for (formal) breeding. However, breeding for quinoa has been mainly done in the informal sector, where farmers have gradually selected better lines.

The crop has become more adapted to drought, low and high pH soils , low inputs and frost. Though the average protein content of the seed is already quite high, it might still be further improved, as variation ranges from 9% to 21% (Fleming & Galwey, 1995)

The Brigham Young University (BYU) has a strong cooperation with the Bolivian breeding program, whereby, the researchers are developing varieties that are genetically diverse, highly productive, and resistant to environmental stresses, insects and diseases and by using genetic manipulation and improved crop management.

Quinoa's local consumption

For the local market, quinoa is produced mainly for human consumption due to its nutritive value. Farmers usually consume the boiled product. In addition, the grains are consumed and processed such as porridge, flour, puff pastry, etc. Young leaves of quinoa can be used as a vegetable crop like spinach, and older leaves as a green fodder crop for animals

Quinoa seeds may contain a bitter anti - nutritive detergent - like saponin molecules in the pericarp of the seed (Johnson & Ward, 1993). Saponins must be removed from the seed before consumption either by washing in water or mechanical abrasion. Washing the seed creates the additional problem of disposing of the polluted water. However, saponins may have uses as foaming agents or as raw material in the chemical/pharmaceutical industry (Fleming & Galwey, 1995). In addition, saponins may act as non-specific pest, birds and disease repellents (Jacobsen et al., 1996).

Quinoa export

About 75 % of the production in Bolivia is sold for local and external market (more than 10.000 metric ton) and the remaining part is used for local consumption. Bolivia is considered to be the first world producer of quinoa followed by Peru. The major export (about 80%) takes place to USA and Europe and exceeds US $ 5 millions annually as organic product.

The price of organic quinoa of the cv. quinoa Real is US $ 1300 /MT while the non-organic seed is sold at the price of US $ 530 /MT.

Quinoa stakeholders in the Southern Altiplano of Bolivia

Due to the socio economic importance of quinoa in the southern Altiplano, we would like to limit our information to this area. The quinoa production chain exists of the producers, industry, intermediates and consumers. In this area, the cultivation of quinoa usually takes place in large number of productive unites, whereby each unites vary between10-15 ha per family. The quinoa producers have no access to adequate technology of applied research, technical assistance, good quality seeds, credit facility, and limited use of certification of organic quinoa. In addition, producers in most of the cases do not respect or comply with commitments to suppliers and consequently loose respect and credibility in both local and international market. Quinoa farmer associations do exist and operate here and there, however, they are not entrepreneurs as they lack experience in marketing and selling their crop at a good price and they lack this vision. Notably, approximately 60 to 70 % of the quinoa producers are independent farmers. It is also important mentioning that quinoa is cultivated as monoculture crop in this area.

The intermediate usually play an important role in commercializing the product and they operate in informal way and they sell their product to the industry. The productive unites are usually scattered and is difficult to reach by the intermediate.

The numbers of quinoa private companies are limited to five to six, whom are involved in absorbing the major volume for the commercialization, cleaning and selection. In addition, there are no incentives from private or public sector to improve the added value of quinoa. In the last years, there is an increase in demand of the quinoa in the international market, especially to USA and Europe for the organic quinoa in the form of pearly quinoa. Despite this fact, no sufficient promotion of quinoa in the external market is implemented.

There is a strong tendency for quinoa producers to focus on the international markers. The local market is often overlooked and we feel that local market should deserve more attention. In addition, if all producers exports quinoa, this might have serious problem on the diet of the quinoa producing communities. For instance, in 2004, the price of quinoa has increased in the international market, consequently, farmers sold most all their harvested quinoa and replaced it by other processed food products for their daily food, especially pasta, that is a wheat product with much lower nutritional value.

In summary, the quinoa production chain is poorly organized and there are great potentials in strengthening the (international) quinoa production chain as well as strengthening local networks.

Farmers demands

In June, 2004, a workshop was organized by PROINPA in Cochabamba, Bolivia. The major problems expressed by quinoa producers were: low soil fertility, drought tolerance, high incidence of pests, mixed of varieties, poor quality seed, poor quality of quinoa, lack of equipments for harvesting and post harvesting, low prices, lack of credit facility and lack of technical assistance and technology transfer.

Farmers prefer low saponine content as it takes less work to process the seeds, while the attack by birds is not so serious (McElhinny et al., 2006)

Marketing in Europe and USA

Consumers in Europe and USA are becoming more critical for the quality of their food, both in terms of nutritive value as well as the production methods. In this respect, quinoa has great potentials, due to its high protein content, balanced amino acid content and it organic production. In addition, consumers may prefer quinoa, when they know that is produced by small indigenous farmers from the Altiplano (fair trade principle). To fully exploit this added value for overseas markets quinoa should be sold as specialty and not as bulk product.

Preduza

Introduction

In the Andean region often low yielding varieties are used, that are highly susceptible to various diseases. As a consequence and also due to poor agricultural practice, many farmers in the Andes do not produce enough food and suffered from malnutrition

In 1997, the Project for Durable Resistance in the Andean Region (El Proyecto Resistencia Duradera en la Zona Andina (Preduza) was initiated. Preduza is a collaborative program of the Laboratory of Plant Breeding of the Wageningen University in the Netherlands and the NARS of Ecuador, Peru and Bolivia. Preduza aims at developing improved food crops varieties that are durably resistant to plant diseases with good level of adoption and well adapted to marginal conditions in the Andean highlands. Through participatory methodology, Preduza make use of agro-biodiversity and the existing local knowledge of the stakeholders to ensure that developed varieties are well accepted by the small farmers. This result in an increase of the productivity of the small - scale farmers, a reduction of the use of fungicides and an improvement of the quality of the food produced and consumed.

The Preduza approach

The Preduza approach is based on the combination of three strategic components which are logically interconnected in the program: the development of durable resistance, the use of local breeding materials and the participation of farmers in the selection in advanced stages of the program.

Durable resistance

Durable resistance is especially beneficial for small-scale farming that is characterized by low inputs, like fertilizers and fungicides. Low input crops are continuously threatened by a wide variety of diseases. Through the development of durably resistant varieties, Preduza aims at improving the yield without increasing inputs of food crops but also to reduce the health risk (e.g. by mycotoxins production by *Fusarium* spp. in maize or by the application of fungicides) of the small farmers and to protect the environment.

Local biodiversity

Making use of screening methodologies developed by Preduza, it was shown that local varieties where often possessing relatively high levels of residual resistance (Danial. 2001) often higher than improved materials.

The Andean Region is highly variable in environmental variation. It is also highly variable in farmer preferences. This is one explanation for the fact that breeding programs have so far been relatively unsuccessful. They were not able to develop adapted materials that meet the variable and cultural preferences of farmers for consumption grains and tubers. For example, both farmers and consumers prefer a soft-maize kernel in their diet, but different dishes are made with different types of varieties. While for potato red-skinned tuber is more preferred than creamy coloured tones. These type of preferences for a complex niches are unimportant at a global scale and, thus, difficult to address by breeding programs with a global mandate. Use of local varieties in crossing programs is one way of dealing with the challenge of generating adapted varieties that are attractive to farmers. The prominent use of local varieties also implies that this breeding strategy has a great potential to contribute to sustainable use of local crop genetic resources.

Participatory plant breeding (PPB)

Farmers' participation is a prerequisite to ascertain that varieties are developed that are demand driven. This was surely not common sense in the Andean region but breeders and farmers have now realized and experienced that farmers' participation is of mutual interest in the development of new cultivars, that are adapted to the local networks or are developed for the international markets. In other words: "farmers' participation is primarily an attitude, while the applied technologies may differ from location and crop". This guarantees the suitability as well as the acceptance of the new varieties. In the long run FPR and durable resistance are a powerful combination for sustainability, ensuring that the farmers accept the varieties and will keep planting them, and that the new introduced resistance will not break down within a short period of time.

Since it is difficult to cater for an agro-ecological and culturally varied Andean Region, decentralization is a condition to make a breeding program more effective in addressing the various niches. This means that breeding objectives and preferences of the various farmer communities in the marginal areas should be studied and determined before designing a breeding program. A breeder should know the special requirements of the niche markets and develop dedicated breeding programs for each of them. However, as breeding is a time-, space and labor consuming process often the niche markets are too small for commercial breeding. The costs however can be significantly reduced if breeders and farmers intensively cooperate. For these practical and economic reasons, farmer participation has become a crucial part of the Preduza approach. In addition of enabling the decentralization, farmer participation in the selection process is also important to ensure the development of materials that are closer to farmers' current preferences.

Quinoa breeding within Preduza

Since 1997 the quinoa breeding program in Bolivia has been cooperated with Preduza. A large collection of 1800 regional landraces had already been build up and initially this collection was screened over several years and generations. The genetic variation for nearly any trait was very great indeed and simple selection methods were applied to select advanced lines. Most emphasis was on resistance to downy mildew (*Peronospora farinosa* f.sp. *chenopodii* (Fr.) Fr). Promising lines have been identified with good grain quality and large grain size. The best lines have been used in the crossing program and for testing jointly with farmers. The cultivar 'Grane Grande' has been released in 2003 and is preferred due to its large grain size that gives a better price in the international market.

One of the future challenges is to bring the seeds of the new cultivars to the farmers. This can be done by the formal sector, but the costs are often too high and farmers are not willing to pay the higher costs of high quality basic seed. Alternatively, farmers may maintain and propagate their own seeds. This requires good management practices to avoid genetic pollution of the new cultivars. Preduza is aiming at a combination of seed production by the formal

sector (NAR or NGO), who produces genetically pure high quality basic seed and one or two rounds of propagation by highly skilled well-trained farmers who propagate for their own region. Such system is already operational for potato seed production in Chimborazo, Ecuador and farmers are happy to buy the seed potato as they have learned that the yield may be increased by several factors (!) compared with the traditional system of seed propagation by each individual farmer. In this way, high quality seeds can be produced for relatively low costs.

Future perspectives

As a result of the implementation of the Preduza approach in practical breeding programs, an economic gain of approx. 125 million US $ could be achieved if the seed of such new varieties is propagated and distributed to farmers (Table 1). Therefore, seed production is very crucial in the coming years to ensure the diffusion of the new cultivars.

Table 1. Potential economic gain of breeding for durable disease resistance in the Andean region if the new Preduza cultivars are maintained, propagated and disseminated to the farmers.

crop	Country	release year	new cultivar name	area x10³ ha	farmes' yield ton/ha	yield gain %	potential diffusion %	US$/ton	potential annual gain US$
Maize	Ecuador	2006	Cross 1 and 2	150,000	0,9	20	15	130	526,500
Wheat		2003	Zhalo	30,000	0,8	200	30	180	2,590,000
Barley		2003	Canicape	60,000	0,8	200	30	200	5,760,000
Quinoa		2006	'575'	5,000	0,6	60	20	500	180,000
Beans		2004	Yungilla + Mille I	20,000	0,8	50	25	650	1,300,000
Potato		2004	Clone 97/11/6'	45,000	0,8	50	25	180	8,100,000
Maize	Bolivia	2003	Sinthetico II	40,000	2,0	75	20	150	1,800,000
Wheat		2006	Jup/ZP//coc3	75,000	1,2	25	30	165	1,113,750
Quinoa		2003	Grane Grande	35,000	0,6	30	20	400	840,000
Potato		2005	Yunguanita	60,000	8,0	15	20	125	1,800,000
Maize	Peru	2004	Complejo I	65,000	0,9	30	25	200	877,500
Quinoa		2004	VESQ-01	40,000	1,0	20	15	300	360,000
									25,249,750

Plant Breeding and Genomics

History of Plant Breeding

As we are at the eve of a new era in plant breeding whereby genomic tools are being developed and exploited, such as in the main agricultural crops like cotton, soya and maize, it is useful to look back in the history of plant breeding to understand the relevance of the present situation.

Plant Breeding started when tribes changed from hunters to agriculturists that grew some wild plants for consumption. People will have realized that to improve the production it is most rewarding to maintain the best seeds for the next crop. This is already the simplest form of breeding: positive mass selection.

In the 19^{th} century gradually seed traders started to improve their varieties. Most varieties were rather heterogeneous, because they were genetically not pure and as a consequence the agricultural performances, like yield, disease resistance and quality, were not optimal. Therefore, quite some improvement could be made by mass selection.

In the middle 19^{th} century Mendel described his genetic theories. It took till the beginning of the 20^{th} century before scientists rediscovered these theories. In the same period breeders started to make crosses between cultivars and employed pedigree selection. When desired traits were absent in the cultivated species but present in wild relatives, interspecific crosses were made to transfer these traits from the wild relatives to the cultivated species. Breeding was still mainly executed by small scale family companies whose main economic activity was selling seeds. But, when these companies realized that breeding gave added value these companies gradually developed into specialized breeding companies.

In the second half of the 20^{th} century breeders gradually took more advantage of scientific research and special training programs were designed to give breeders a better training in important disciplines like agronomy, genetics and statistics. In the 1960s the first hybrid cultivars were produced from crosses between true breeding lines or between inbred parents of normally cross pollinating crops. Because of the strong vigor and uniformity, hybrids were superior over open-pollinated cultivars as well as over true breeding cultivars. Hybrids are superior over true-breeding cultivars as they combine more useful agronomic traits and they show increased yield because of their heterozygous nature (heterosis). These added values were so great that farmers prefer to buy hybrid seeds even when they are much more expensive as they got a good return (higher economic value) of their investments (high seed prices). In

addition, it is very unattractive for farmers to propagate the seeds of a hybrid cultivar for next season as the progeny seeds do not show the characters of the seeds of the parent hybrid cultivar. This is due to the heterozygote nature of hybrid that causes segregation of the useful agronomic traits in its progeny. This system of increased interdependence of farmers and breeders in the hybrid seed business has been very successful as the farmers continuously could get improved seeds and the breeders earned enough money that they can invest in expensive breeding programs to develop the improved seeds.

This system also requires that producers are able to do the investments in the basic seed. The entrepreneur-producers easily see the added value of hybrid seeds and have the resources to do the required investments. Marginal farmers often are focused to solve the problems of today or tomorrow and do not have the (mental and financial) capacity to invest in expensive seeds. Therefore, hybrid cultivars are mainly used by the more resource-rich farmers.

In the 1980s the fast developments in molecular biology offered great potential for plant breeding. Traditionally, plant breeding could only benefit from the natural variation for agronomic traits that was available within the crop species or in related, crossable species. With the advent of molecular biology any gene of interest could be transferred from whatever organism to cultivated crop species. Such product with an alien gene was designated "transgenic crop" This technology offered great perspectives as it allowed breeding to pass the natural barriers that restricted the genepool of breeders to the germplasm of crossable species. This was unprecedented and caused large concerns in society, as there was much concern on the risk for the environment and human health. In addition many citizens principally disapproved these techniques as they were "not-natural". Last but not least the first transgenic crops offered added value for the producers but not for the consumers, who consequently did not see the advantages for them of these unnatural technologies. The European consumers were most concerned about these new perspectives of genetically modified organisms (GMO) and banned the practical usage of GMO's. Nowadays transgenic crops are hardly grown in Europe though the area of GMO's in the rest of the world is steadily increasing and has reached the level of 44 million of hectares in 2005, Fresco, http://www.fao.org/ag/magazine

Molecular techniques have further evolved in the last decades of the 20th century, but in the present millennium the developments and achievements in biological technologies go so rapidly that it resembles the digital revolution. The appearance of a new ("omics-") vocabulary reflects the general opinion that a new era in molecular biology has been reached with great implications in science and society (or that biologists want to show that they are trendy). Anyway, genomics may influence any biological aspect of science and society, like for forensic applications, medical science, nature management, agriculture etc.

How does genomics effect plant breeding? Plant breeding is based on the selection of superior genotypes in the progenies of selected parent plants. However, usually the plant breeder does not know the genotype as he/she can only see the plant in his environment (phenotype). Therefore, the art of breeding is recognizing the "genotype behind the phenotype". It is obvious that knowledge of genetics and also genetic tools are very helpful in increasing the efficiency of breeding programs. As long as breeding is for simple inherited traits, this can be regarded as reductionistic. However, a breeder always has to consider the complete genetic make-up of a plant, as a cultivar has to meet many constraints that farmers and other stakeholders demand.

Genomics is the study of genes, gene expression and functioning of cellular pathways at the level of the organism. It encompasses the complex interaction at all levels of biological information: DNA, mRNA, proteins, metabolites and how these informational networks work together. The added value of genomics for plant breeding is that the selection of superior genotypes can be done more efficiently. This may reduce the costs of breeding programs or allow the selection for traits that could otherwise not be done. This is mainly applicable for quantitative traits that are often controlled by many genes and the expression is usually dependent on the environmental conditions.

Genomics provides the breeder with a richer toolbox, that he will use to design optimal breeding programs based on his knowledge of genomics results and of the market. This makes the breeding so complex that highly trained specialists are needed to support the breeder. But now more than ever, the breeder can design his breeding programs for large commercial markets or for marginal markets like in the Andes. A commercial breeder has to focus on the first market. Breeding for niche markets will rely more on joined efforts of (non-commercial) breeders with farmers. This is a challenge for the quinoa local networks. Plant breeders have continuously been adapting in implementing new tools and technologies in order to select superior genotypes. The implementation of genomics is the next step in this continuous process. It does not change the principle of plant breeding nor does it expand breeding beyond the germplasm that has always been available for breeding.

Plant genomics in the Netherlands

The Netherlands has a strong position in plant sciences with the strongest concentration in Wageningen, that ranks third in the world. Also the breeding industry has a strong international position, especially in horticulture and potato. The main genomic researchers in these crops and in *Arabidopsis* have combined their efforts in the Centre of Biosystems Genomics (www.biosystemsgenomics.nl) with a strong emphasis on public private partnerships. *Arabidopsis* in used as reference species for the other crops. This approach will ensure that the results of these studies will have a crop specific impact as well as more generic impact for other crop species, including quinoa. The research themes are quality and resistance and the technical fields of interest are structural genomics (sequencing), transcriptomics, metabolomics and proteomics. This initiative places The Netherlands even more in the frontline of plant genomics research leading to international initiatives like sequencing the tomato and potato genomes and European research programs like Bioexploit and EU-Sol. As a result there is an excellent infrastructure both in equipment as well as in human resources in plant genomics in The Netherlands. This provides a good knowledge and technology infrastructure in genomics that is very suitable platform to build other international cooperations in other crop species like quinoa and with other partners like the Andean countries. We believ that The Dutch public private partnership in the field of plant genomics have a responsibility to apply their knowledge and techniques for commercial interest as well as for international cooperations with the less resourceful countries in the world.

The goal of the Centre for Biosystems Genomics (CBSG) is to contribute to the sustainable quality improvement of food crops and their derived products for the consumer and the environment. We will achieve this by elucidating the molecular and ecological mechanisms of plant-pathogen interactions and the interacting biological components that determine the quality of crops and derived products. Our genomics program will yield new genetic markers that contribute to sustainable agro-production. The further development of marker-assisted breeding will provide new opportunities for crop improvement without genetic modification. The option of genetic modification will be used for research purposes but will not be commercially exploited without close consultation with all stakeholders in society.
(Businessplan CBSG, 2002).

Genetic research on quinoa

The Brigham Young University, College of Biology and Agriculture (BYU) has an extensive cooperation in genetic research with the national quinoa breeding program in Bolivia whereby half a dozen US scientists are involved and that is funded by McKnight foundation (www.mcknight.org). The research focus is on the development of (1) molecular markers (2) the mapping of important agronomic genes and (3) the structural and functional analysis of these genes.

A rather dense molecular marker map of quinoa has been generated with 230 AFLP-markers, 19 SSR-markers and six RAPD markers. The map spans 1020 cM and contains 35 linkage groups with an average marker density of 4.0 cM (Maughan et al., 2004). These marker analyses are being extended with more SSR markers and with generating a new segregating population of recombinant inbred lines (RILs). In addition, a Bacterial Artificial Chromosome (BAC) library is under construction with a 10x genome coverage (Colemanm BYU, USA) and an EST database is available to be used as markers on the quinoa genetic map. BYU may also provide genetic information that will be useful in studying important agronomic characteristics of quinoa such as the quantity and quality of seed protein. The aim of this research is to support the national Bolivian breeding program to develop new cultivars that are preferred to by the farmers. A tripartite American, Bolivian and Dutch partnership will give a boost to this research that will maximally benefit from the expertise of these three partners. This may greatly encourage the breeding programs as well as provide a platform for training of young researchers from these countries.

Participatory genomics research in quinoa

It is clear that the application and implementation of genomics in the local quinoa production networks and global production chain has to be attenuated to the stakeholders' demands. This implies a co-creation between producers and other stakeholders and researchers: genomics can influence participatory breeding as well as farmers can influence the application of genomics. The first aspect implies that genomics can provide the tools and techniques to optimize breeding programs, while the second aspect implies that farmers can set the research agenda for genomics researchers to develop the tools and techniques that are addresses to their needs. To achieve such co-creation we see

that at least four elements are crucial for successful participatory genomics in quinoa:

Participatory organization

A participatory organization of all stakeholders should be build to set the research agenda. These stakeholders may compass genomic researchers, geneticists, breeders, phytopathologists as well as farmers, traders, retailers, processors and consumers. Such organization has a strong mandate to make important decisions in management and policy of genomics research programs. As genomic research has already achieved major assets and the main stakeholders in the quinoa food production networks and chains are known, the participants of such organization can easily be identified and the organization be settled. This will maximize the change that the research investments will be beneficial for the stakeholders. Such organization will also contribute to the empowerment of the farmers

We propose to apply an interactive food supply chain approach on plant genomics developments related to consumers, retailers, processing industry, farmers, and plant breeders. The food chain approach is used because its starting point is 'chain reversal', consumer preferences and concerns are predominant in product development. An interactive approach is used because the competition and co-operation based on contracts, the normal supply chain approaches, do not seem to work.
The overall aim of the project is to understand how plant genomics can be used in the food chain to accommodate consumer preferences and concerns
Bart Gremmen, Wageningen University

Stakeholders' preferences

To define the genomics research goals all stakeholders express their demands for the traits of the quinoa crop and the performance of the quinoa products in the food networks or chains. The above mentioned participatory organization designs a research program based on these demands as well as on the technical potentials of genomics tools. This will lead to a fine-tuning between the genomic potentials and the demands of the producers and markets.

Research in Bolivia

Preferably, all research should be carried out in Bolivia by the national researchers. Technical backstopping might be provided when required. Technologies should be used that can be applied in Bolivia. Some infrastructure is already available at the national breeding program of Proinpa, but, if needed, additional investments in infrastructure are done. Great care should be taken that these investments are integrated in the research facilities of the research institute, in order to guarantee that the technologies and tools can be applied in a sustainable way.

Andean countries are very concerned about the conservation of their Biodiversity and are very restricted to exchange genetic materials. This also holds for quinoa as attempts have been made to file a patent on quinoa by a foreign research institute. Bolivia has considered this an act of bio-piratism and does not allow any transfer of quinoa germplasm out of the country. The International Treaty on Biodiversity has set rules for exchange of endogenous and unique germplasm but this has not resulted in usage of these germplasm in international research yet. When the research is carried out in Bolivia, there is not the risk of the export of useful genotypes or genes and this will also increase the independence of the quinoa research program.

Capacity building

For a sustainable impact of research investments, highly skilled, experienced and motivated professionals are needed. Therefore, also tailor-made training courses should be organized for the main researchers and technicians involved in this research. In addition, together with farmers, experiments are set up to improve the (basic) seed production system, quinoa production, storage and transport. Though the genomics research is most concentrated at the early stages of the genomics breeding program and hence also at the earliest steps in the quinoa production networks and chains, for the successful implementation of genomics research also these later steps in the quinoa production networks and chains have to be taken into account. The behavior of new genomics products should be followed throughout all stages of the production networks and chains to satisfy all stakeholders. As far as new technologies have consequences for the routine handling of the quinoa crop and /or product, training programs are organized to disseminate the new knowledge and technologies.

Preliminar research plan

So far, the general conditions for the implementation of genomics to strengthen the quinoa production chain are mentioned. But is such research plan realistic? Are there already genomic techniques available that can be implemented under the conditions described above?

We believe that the most suitable short term technology that can already be applied in the quinoa breeding program is the usage of molecular markers. In quinoa, different types of markers have been generated by the Bingham Young University (see above), that can be applied in Bolivia. This does not only hold for the knowledge (molecular marker specifications, sequences, map positions, etc.) but also for the technical methods and infrastructure needed to implement these markers. A typical program should start with the definition and articulation of the needs of the stakeholders in the production chain. Based on there demands a research program is formulated aimed at the development of diagnostic markers for these preferred traits (*target traits*). Crucial elements for the design of such research program are the availability of genetic variation in the existing germplasm (*phenotyping*), the availability of informative molecular markers for this germplasm (*genotyping*) and the target groups (locations, position in the production chain or in the local network) that will benefit from this research (*marketing*).

An initial screening (phenotyping and genotyping) with the locally available germplasm, including the best cultivars that are used by the farmers will lead to the identification of parents for the genetic research, that already have high agricultural value but are contrasting for the target traits. A large collection of genetically well defined quinoa lines from the Bolivian national breeding program is available and this collection is evaluated with the farmers in the farmers' fields. This strategy proved to be successful especially in marginal areas through the use of local material and with the participation of farmers). These evaluations will also include quality and processing evaluations by local farmers and consumers, but also by consumers at the end of the international quinoa production chain, in Europe and USA. The same collection will be DNA fingerprinted for a genetic analysis.

The same collection is DNA fingerprinted to identify genetic relationships between the lines of the collection. This information is crucial for the selection of the genetically most contrasting parents that also are contrasting for the target traits. If needed also parents are included with lower agronomic value but that have a high value for the target trait as these can be used as donors of such traits. Subsequently, crosses are made and segregating progenies are phenotyped and genotypes again to study the genetics of the traits and to identify markers that are linked to these genes. Such markers can be used directly as diagnostic markers or converted into other types of markers that are most easy to handle in a breeding program in Bolivia. This is then the basis for a practical breeding program whereby the laboratory researchers do the genotyping and the breeders are responsible for the breeding program whereby farmers participate in the selection of the best advanced lines. The quality of the products is assessed with other relevant stakeholders, like consumers in local networks and processors, retailers and consumers for external markets.

When new cultivars have been released a seed production system has to be settled to provide high quality seeds to the farmers for relatively low costs. Preduza has experience with good partnership of the formal and the informal sector, that can be implemented fro the quinoa basic seed production in Bolivia. This is not a dogmatic system but forms more a blueprint with room for variances as the cultural differences between the regions should be taken into account.

The molecular techniques have greatly been improved in the last decade and can relatively easily be applied in rather basic molecular labs. An additional advantage of using molecular markers is that breeding can continue as it has been in the last 5000 years (see above), which may contribute to a good public acceptance. We favor this approach as it combines modern technologies (DNA fingerprinting) with endogenous local knowledge of the farmers. The main interventions (marker analyses) are mainly at the start of the breeding program and farmers do not have to be involved in the application of the technology as this is done by trained laboratory people. The output of this research will be new cultivars with added value for farmers and other stakeholders in the local quinoa networks or in global quinoa production chains. The cultivation and further processing of these new cultivars can be done in the traditional way, but does not exclude other innovations in later steps of the quinoa production network or chain.

The role of Preduza is to bring the stakeholders and technologies together and to monitor the research and development process to ensure that the investments and efforts are demand driven and beneficial for the marginal farmers of the Andean highlands.

Conclusion

Agricultural production systems in developing countries are complex and diverse as many farmers are small scale and resource poor. We believe that we should respect these traditions and implement new technologies with minimal impact on the traditional way of quinoa production, processing, marketing and consumption. There are good potentials for the implementation of genomics in agricultural research and development programs that fit in this philosophy, like explained above.

Genomic research is taking place primarily in developed countries and our challenge at present is to design an innovation system that focuses this potential on the problems of developing countries.

It is clear that genomics cannot overcome the gaps in infrastructure, regulation, markets, commercialization, seed system, and extension services that might hinder the delivery of agricultural technology to the marginal poor farmers and therefore a genomics research plan should go together with other activities to strengthening the quinoa production chain. From users' perspectives, breeders, farmers, retailers, consumers, public and private sector should be included.

Capacity building of all stakeholders including researchers and technicians in genomics should be a priority to ensure that scientists from developing countries have the knowledge and experiences necessary to make their own decisions regarding the use of biotechnology.

Finally, clear genomics research projects are already feasible based on current knowledge and infrastructure. The genomics technology of first choice is the usage of molecular markers as the required technologies are relatively easy applicable in Bolivia and can successfully be integrated in quinoa breeding.

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