Potato Research (2017) 60:361–381
https://doi.org/10.1007/s11540-018-9389-9

Breeding Differently: Participatory Selection and Scaling Up Innovations in Colombia

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Received: 9 September 2017 / Accepted: 30 May 2018 /
Published online: 27 July 2018

Abstract Global challenges like sustainable development, climate change, malnutrition and gender inequality can be tackled from an agricultural perspective. Micronutrient deficiency is a major problem for the health and food security of the population. In Colombia, iron deficiencies affect 32% of the children under the age of five; and 43% of the Colombian population have zinc and vitamin A deficiencies. We designed and implemented a research-for-development programme that links agriculture and nutrition through a two-stage project. In the first stage, we selected three new yellow potato cultivars with better nutritional contents, higher yield and better resistance to late blight than the traditional yellow cultivars. We characterized the Colombian germplasm, *Solanum tuberosum* Group Phureja, for its nutritional attributes. During this stage, studies of the social and nutritional status of the communities were also conducted. In the second stage, we focused on scaling up new potato cultivars to reach potato producers and consumers by promoting the production and marketing of good quality seed potatoes, by establishing four Rural Entrepreneurs Nuclei. The programme promotes gender equity, good dietary habits, the consumption of more nutritious potatoes and empowers local leadership to strengthen governance. Field work was conducted in southern and central regions of Colombia by employing social strategies such as the Family Farming Community Schools. In 50% of the cultivated area, we are replacing the originally used traditional yellow potatoes by the new, more nutritious, potatoes to reach 6 million consumers. A good quality seed system for small-scale potato growers has been implemented. These achievements have been reached through a comprehensive approach in a period of two years.

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Keywords High-quality potato seeds · Innovating in sustainable and nutrition-sensitive agriculture · Participatory research · Social innovations

Abbreviations

AETs	Agronomic evaluation trials
FFCS	Family farming community schools
FFS	Farmer field schools
FSN	Food security and nutrition
Leadership Schools SFSN	Leadership schools in sovereignty and food security and nutrition
REN	Rural entrepreneurs nuclei

Introduction

Humanity is facing various challenges and experts from different disciplines across the world have analysed and proposed strategies to face them. An example is the Millennium Project, which proposes 15 challenges that cover a wide spectrum of areas and sectors, such as sustainable development, climate change, economic inequality, health issues, education, peace and conflict, gender inequality and global ethics (Glenn et al. 2015). Some of these challenges can be tackled from an agricultural perspective through innovative solutions, not only because they directly affect the agriculture, but also because agriculture is an eminently human activity that can promote important changes to benefit the society.

Despite the advances in economic growth that Latin American countries have recently experienced, the impacts of these have been uneven, and unacceptable rates of poverty are still present. Poverty is associated with high rates of unemployment and social unrest. Colombia has shown important improvements in the Global Hunger Index, but still has high stunting and hunger rates among children (von Grebmer et al. 2013). ENSIN (2010) reported that 4.6% of the children are overweight in Nariño in 2010. Malnutrition, especially in children and women, has serious impacts for social and economic development of the country.

Micronutrient deficiencies are a major problem for Food Security and Nutrition (FSN) and overall health for the population (Andre et al. 2007a; Godfray and Garnett 2014; Kubow et al. 2014). The nutritional problem with the highest prevalence in Colombia is anaemia: more than 32% of the population under 5 years of age have iron deficiency anaemia and more than 43% of the population have micronutrient deficiencies such as zinc and vitamin A (ENSIN 2005, 2010). In rural areas, this problem is even more severe. Several micronutrient deficiencies and the highest prevalence of malnutrition among children are found among indigenous and Afro-descendant populations (ENSIN 2010). Nariño rural communities have the second highest malnourished percentage of people in Colombia and 67.7% of the households suffer from food insecurity, compared to a national average of 42.7%; not to mention, food insecurity in rural areas is even higher.

The potato offers an important opportunity to improve the nutritional situation in Colombia because the potato is an important staple food and is the third most consumed food in the world (FAOSTAT 2015). Therefore, potatoes can play a significant role in

addressing food insecurity and nutritional problems, which are the major causes of the global health challenge. The potato, in addition to being a source of energy and fibre, has important nutritional traits (Clayton and Percival 2000; Andre et al. 2007a; Nassar et al. 2012; Ezekiel et al. 2013; Peña et al. 2015) and contains health-promoting compounds such as polyphenols and chlorogenic acid (Andre et al. 2009; Kubow et al. 2014; Liyao et al. 2016; Piñeros-Niño et al. 2016). Because of its high consumption and its nutritional attributes, and because it is the economic axis of thousands of small-scale producers, the potato is a crop that can effectively link agriculture and nutrition and achieve an impact in the rural sector.

According to estimates, in Colombia, about 90,000 families are engaged in potato cultivation and depend on cropping potato (Rodríguez-Quijano 1992) as the means of sustenance. However, potato cultivation is seriously affected by phytosanitary problems and low productivity because of poor seed quality. In Colombia, only 2 to 5% of farmers use certified seed potatoes and, for the case of yellow potatoes, no certified seed is produced, thereby leading to a high vulnerability for this sector (Espinal and Martínez 2005; MADR 2016). Small-scale potato farmers represent 95% of the population growing potato but each one of them cultivates less than 3 ha. This group consists of 85,000 farmers and produces 45% of the total potato production (Monroy-Medina et al. 2015). In Colombia, there are essentially two kinds of potatoes for commercial planting: the tetraploid cultivars, which represent 90% of the cultivated area with an average yield of 20.8 t/ha, and the diploid cultivars, or yellow potatoes, which belong to Group Phureja. Yellow potatoes represent 10% of the cultivated area with an average yield of 12.0 t/ha (Monroy-Medina et al. 2015).

Through agriculture, we can influence nutritional improvement through various means, such as improving productivity. By doing so, the income of families will increase and therefore will allow them to acquire better food in greater quantities. However, the literature demonstrates that higher income and greater availability of food alone do not guarantee nutritional improvement since there are other important factors to consider, such as who handles family income, eating habits and food quality.

In this paper, we present a research-for-development programme that links agriculture and nutrition as a contributing factor to FSN. The research developed was conducted within the framework of the projects SAN-Nariño and More Nutritious Potatoes. We developed and delivered three new potato cultivars: Criolla Dorada, Criolla Ocarina and Criolla Sua Pa. These cultivars have better nutritional quality with higher contents of iron and zinc, a higher yield and better resistance to late blight. We are scaling up these new cultivars by promoting their cultivation with high-quality potato seeds, and their consumption within a diverse diet and good food habits. We present and discuss methodologies and strategies to ensure that these new potato cultivars are sown and consumed in Colombia, all while emphasizing participatory research and social and gender equity.

Methodological Approach for Linking Agriculture and Nutrition with a Focus on Participatory Research

To link agriculture and nutrition with a participatory research approach, we developed a two-stage research programme. In the first stage, we developed an agricultural

innovation consisting of three yellow potato cultivars with better nutritional contents, higher yield and better resistance to late blight. We studied the Colombian germplasm belonging to *S. tuberosum* Group Phureja, adjusted the methodologies for its nutritional characterization and studied the social and nutritional status of the communities involved in this programme. In the second stage, we focused on the scaling-up of new potato cultivars to reach many potato producers and consumers in Colombia.

Figure 1 outlines the general scheme for the methodological approach.

Localization

Field work for the first stage was conducted in Southern Colombia in the province of Nariño, more specifically, in the rural area of the municipalities named Tuquerres, Carlosama, Guachucal, Cumbal and Pasto. These municipalities are in the Andes and are characterized by the fact that potato crop is the axis of the economy. The population in these areas is vulnerable because of their poverty and also for their ethnic origin, since the majority of the population is indigenous.

The field work for the second stage was conducted in the aforementioned localities and also in the central region of Colombia. These locations included the municipality of Sibate in the province of Cundinamarca, and Pasquilla, a rural area of Bogotá.

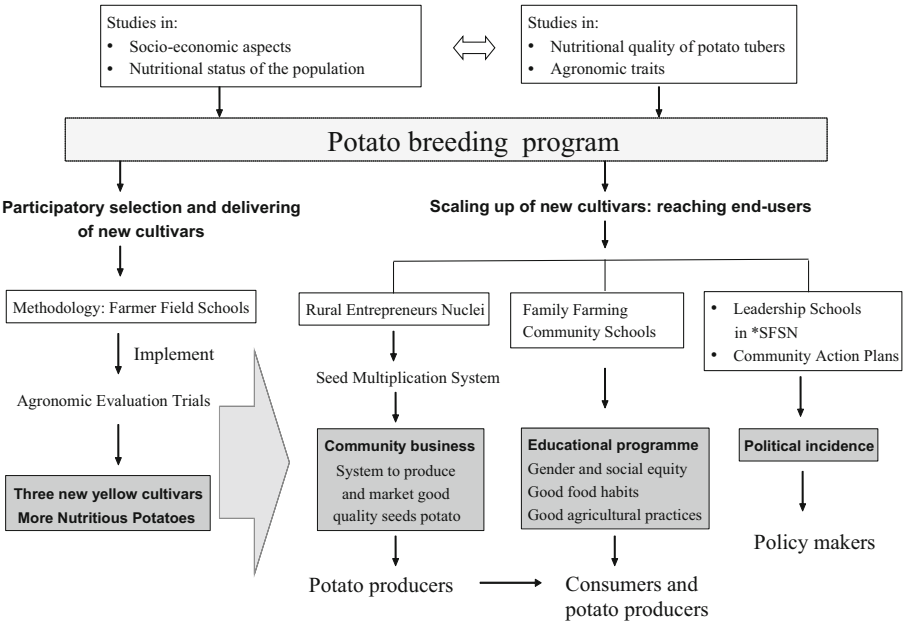

Fig. 1 Methodological approach followed in the agriculture and nutrition linkage programme. The two stages of the programme are identified in bold letters. In clear boxes are the methodologies applied employing participatory research; in grey boxes the main results are presented. At the top are the different studies conducted that are integrated in the central box labelled as "Potato Breeding Program." The arrows indicate the flow followed. *SFSN: Sovereignty and Food Security and Nutrition

Plant Material

The plant material used belonged to the breeding programme at the National University of Colombia; it is referred to as the "Potato Work Collection" and consisted of 104 accessions, 20 landraces collected in Nariño, eight advanced clones (including the three cultivars delivered: Criolla Dorada, Criolla Ocarina and Criolla Sua Pa) and four commercial cultivars, named Criolla Colombia, Criolla Galeras, Pastusa Suprema and Diacol Capiro. These cultivars were employed as controls in the experiments. In total, 136 genotypes were analysed for their nutritional compounds and for their agronomic traits.

Studies for Determining the Nutritional Status of the Population

We analysed a representative sample of 871 households, both urban and rural, from the municipalities of Carlosama, Cumbal, Guachucal, Tuquerres and Pasto and we applied the methodology referred to as 24-h dietary recall (Guthrie 1984). Twenty-four-hour dietary recall is a structured interview to capture detailed information about all foods and beverages consumed by the respondent in the past 24 h. We took anthropometric data for different age groups (Del Castillo-Matamoros et al. 2014a, b).

Studies for Determining the Nutritional Quality in Potato Tubers and Impact of the More Nutritious Potatoes on the Accumulation of Iron in the Blood of Children

Nutritional Quality in Potato Tubers

The nutritional quality was determined in unpeeled and boiled potato tubers that are typically consumed in Colombia. In order to prepare the samples, the tubers were washed and classified according to the size based on equatorial diameter. The tubers were boiled at 92 °C with different volumes of potable water according to their equatorial diameter for 20, 25 or 30 min. The tubers were then cooled in an ice bath for 5 min and were allowed to dry at room temperature. A sample was taken to determine water content and the remaining material was cut into slices, frozen in liquid nitrogen, and stored at − 80 °C. The frozen material was freeze-dried, ground using a domestic blender to less than 0.2 mm particle diameter, enclosed in sealed polyethylene bags, and stored in a desiccator at room temperature until use (Peña et al. 2015; Duarte-Delgado et al. 2016). The nutritional components were analysed according to the methods recommended by the Association of Analytical Chemists (AOAC 1995). The lyophilized samples for each genotype were analysed for macro- and micronutrients (Peña et al. 2015), polyphenols (Piñeros-Niño et al. 2016) and for their functional ingredient properties (Liyao et al. 2016).

The Effect of the More Nutritious Potatoes on Iron Accumulation

A clinical study was conducted to evaluate the effect of the more nutritious potatoes on the nutritional status of the population (Bustos 2015). The study was conducted with children under the age of 5 years old in collaboration with the Colombian Family

Welfare Institute to reach the children of the official restaurants. Two treatments or groups constituted the experiment: a control group with 117 children, who were being fed the regular menu served in school restaurants and a treatment group with 127 children. In this group, the traditional white potato that was present in the menu was replaced by the more nutritious potato. We employed only one cultivar, Criolla Ocarina, which presents the highest contents of iron. The indicators measured were haemoglobin, ferritin, transferrin and the anthropometric variables weight and height.

Studies to Determine Agronomic Traits: Yield, Resistance to Late Blight and Tuber Quality

The evaluation of agronomic traits was conducted through the Agronomic Evaluation Trials (AETs) and followed the Colombian regulations presented in the Regulation 04000 (ICA 1997). The AETs were carried out in 11 localities in the Nariño province and the central region of Colombia during two crop cycles in 2012 and 2013. A total of 22 AETs were implemented with the approach of participatory selection. Eight advanced clones were evaluated in the AETs. The AETs were established with a complete randomized block design with four replicates. The experimental unit consisted of plots of 40 m^2 with a distance of about 1.2 m between rows and a plant distance of about 0.3 m within rows and a total of 120 plants per plot. Yield was calculated at the time of harvest, and the tubers were classified and weighed according to their size in four categories: zero (diameter > 6 cm), first (diameter ≥ 4 cm, ≤ 6 cm), second (diameter ≥ 2 cm, ≤ 4 cm) and third (diameter < 2 cm). The total yield was the sum of all four categories.

The evaluations for late blight resistance were conducted under field conditions in two localities, independently of AETs. One of them was a natural hot spot for this disease in Rionegro, Antioquia, and the other one was Subachoque (in the central zone in Colombia). The progress of the disease was measured weekly during 6 to 8 weeks using the Percentage of Direct Visual Estimation (PDVE) (Yuen and Forbes 2009) and the area under the disease progress curve (AUDPC) was calculated (Campbell and Madden 1990) from PDVE values (Álvarez et al. 2017). The phenotypic data were analysed in a genetic association study to identify Simple Sequence Repeats (SSR) markers associated with this trait (Mosquera et al. 2016; Álvarez et al. 2017), and a non-targeted metabolomics approach using high-resolution liquid chromatography coupled to high-resolution (Orbitrap) mass spectrometry was used to dissect the quantitative resistance observed in the Colombian diploid potatoes (Yogendra et al. 2014a, b).

Participatory Research in the Selection of New Potato Cultivars

The participatory research was developed in two stages. The first stage consisted of the whole period for selecting the new potato cultivars (2012–2014), and the second stage (2015–2017) was the period for scaling up the new potato cultivars (Fig. 1).

From the Farmer Field Schools to the Family Farming Community Schools

In the first stage, we implemented the Farmer Field Schools (FFSs), following the FAO methodology (Ardón 2003). The FFSs were organized in relation to their axis in the

research conducted in the AETs; therefore, small-scale farmers and the scientific team worked together. The AETs considered different social and cultural contexts. In each locality, agreements were reached regarding crop management and agronomical techniques by following farmers' criteria for cropping. Furthermore, technical supervision was carried out for pest control and crop fertilization. A base line was established to understand the farmers' knowledge of the potato crop and their additional interests. The base line allowed a participatory curriculum to be built where the scientific team introduced various topics. In addition to the topics related with good agricultural practices, some new topics such as food security, nutrition and gender equity were introduced. Each FFS involved about 40 farmers who designated a coordinator team and a president with precise responsibilities for contributing to the organization and running of the school. The FFSs established some rules related to division of labour, management of funds and aspects that the school members considered essential for getting a good understanding of one another.

For the second stage, we developed the Family Farming Community Schools (FFCSs). These schools take the fundamentals of the FFS, but were evolved to work with the whole family. Children, youth and women are targeted to strengthen their capacities and promote good eating habits and practices that promote social and gender equity. Training in advocacy and entrepreneurship are developed to promote the construction of sustainable businesses and social change. The schools' activities were focalized to promote the cultivation and the consumption of the new "More Nutritious Potatoes" in the framework of a diverse diet. The FFCSs were implemented in two cycles. In the first cycle, the members of the schools developed and agreed upon an educational programme that established links between agriculture and nutrition. The first cycle was implemented in a period of 10 months. The major activities developed were theoretical-practical workshops, communitarian work (indigenous name: *minga*), establishment of home gardens (indigenous name: *shagra*), the Communitarian Fairs (*EcaFerias* in Spanish), and inter-institutional dialogue. The inter-institutional dialogue is promoted especially for the methodology referred to as "Leaderships Schools in Sovereignty and Food Security and Nutrition" (Leaderships Schools in SFSN). The first cycle of FFCSs ended with the proposal of the Community Action Plans (Fig. 1). The second cycle of FFCS was implemented in a period of 10 months. During this period, the members of the schools implemented their Community Action Plans; these plans primarily focused on solving the needs of the whole community.

Participatory Research in the Scaling Up of New Potato Cultivars

Scaling Up of More Nutritious Potatoes

The methodologies for scaling up stress exchange of knowledge among researchers and communities and the promotion of social change. The methodologies included the following: (a) establishing real trans-disciplinary approaches to link agriculture and nutrition; that is, approaches where everyone contributes and learns; (b) approaches that favour educational methodologies that facilitate the autonomous development of individuals and organizations; (c) the construction of concerted partnerships between different stakeholders to expand impacts and facilitate sustainability; (d) the linkage

of women as strategic agents for change and social development; (e) the importance of combining ways and means of communication to ensure that potential beneficiaries receive quality information and reach the maximum of end-users.

To attain a wider impact on consumer population with the more nutritious potatoes and to strengthen the small farmers' capacity to take advantage of this innovation, we designed a scaling-up model that considered potato supply, marketing and demand and related public policies. This model included (i) partnerships and institutional collaboration to promote adoption of the innovation among small-, medium- and large-scale farmers; (ii) to develop an innovative educational programme promoting the consumption of the new potato cultivars, as well as better food habits in the most vulnerable sectors of the target population and (iii) to attain political impact by empowering local leadership to strengthen governance.

We considered four fundamental elements for scaling up the more nutritious potatoes: (1) supply; (2) marketing; (3) demand; and (4) public policies.

Supply and Marketing of More Nutritious Yellow Potatoes

To guarantee the scaling up of the new yellow potato cultivars at the national level, we selected four potato producers' organizations and empowered them to develop a high-quality potato seed system in Colombia. These organizations are in the south of Colombia in the municipalities Tuquerres and Pasto (Nariño), in rural Bogotá (Pasquilla) and in Cundinamarca in the municipality of Sibate. These organizations have been strengthened in management and organizational practices to produce and market high-quality potato seeds through the Rural Entrepreneurs Nuclei (REN) methodology (Parrado et al. 2009), conforming four REN (Fig. 1). This methodology emphasizes autonomous capacity development by training in seed production techniques, planning of production, short market chains linking seed potato producers with potato producers taking advantage of existing short market chains and the development of new market chains such as farmers markets and *EcaFerias*. The training processes go along with the development of the business. The REN started the seed potato production with mini tubers obtained from a private company specialized in micro propagation, which guaranteed the mini tubers were disease-free and followed the rules established in Colombia (ICA 2015a, b), by the Regulations 3168 and 3888. The REN multiplied the seed potato in seed categories: basic, registered and good quality. Potato producers buy good quality potato seeds for planting and produce fresh potato for consumers in the south and central regions of Colombia.

Potato Demand and Public Policies

Additionally, more nutritious potatoes in the regular diet will increase micronutrient intake and mitigate hidden hunger without added costs to the families; there will be no cultural changes imposed. A better family income and availability of more nutritious potatoes are not enough to overcome undernutrition in small farmers' families. Therefore, we established a strategy to educate local communities to (1) increase food diversity by developing home gardens, promoting the recovery of healthy ancestral practices and protecting native seeds; (2) to provide micronutrients powder supplementation for critical population groups (pregnant and lactating women and children under

five); (3) to improve sanitary conditions including: deworming, home fortification—micronutrients, improvement of basic sanitary conditions and support for adequate access to health services; and (4) training in food and nutrition education in the context of the home, in conjunction with the FFCSs.

In order to influence public policy, we have developed Leaderships Schools in Sovereignty and Food Security and Nutrition (Fig. 1) to train local leaders in FSN technical knowledge and in capacities to engage in dialogue with the authorities and represent the interests of the communities.

The cumulative evidence on the coexistence of undernutrition and obesity requires an approach that promotes the consumption of a more diverse diet and physical exercise. In this regard, the improvement of the families' education and women's empowerment allow the carrying out of interventions that promote the production and consumption of nutrient rich foods, as well as the use of improved food preparation and child care practices.

Results and Discussion

We developed a programme for research-for-development to alleviate the food and nutrition insecurity through the potato breeding programme. In participatory research, farmers and the scientific team selected three potato cultivars named Criolla Dorada, Criolla Ocarina and Criolla Sua Pa. These cultivars are simple hybrids and present improved nutritional quality and improved agronomic traits. These cultivars are yellow potatoes that belong to the Group Phureja.

The programme also addressed the scaling up of these cultivars in Colombia in order to reach potato growers and consumers by implementing a comprehensive strategy to link agriculture and nutrition through the generational knowledge from social and natural science. Consequently, the programme made an impact on the potato breeding programmes and, especially in the rural sector, promoted social change. The implemented strategy employed diverse previously developed social methodologies such as FFS, REN, Leadership Schools in SFSN and developed the methodology called FFCS (this paper) for working with the whole family.

Food Insecurity and Nutritional Status of the Population

The results of the analysis of 871 households belonging to the five Andean municipalities in Nariño described previously highlighted the high incidence of food insecurity (Fig. 2) that reached 96.7% in Cumbal, which is a municipality that is eminently indigenous. These families had low incomes; 82% of them received an income less than one legal monthly minimum wage. This is considered the major cause of food insecurity.

The results regarding deficiencies in the intake of nutrients for the population and the nutritional status for children under the age of five are shown in Tables 1 and 2. This data reveals a lot about the serious nutritional situation for the targeted population. All the age groups have intake deficiencies for calories, proteins, minerals and vitamins. Twenty-nine percent and 91% of the population have deficiencies in iron and zinc, respectively. Iron deficiency is the most prevalent nutritional deficiency and the main

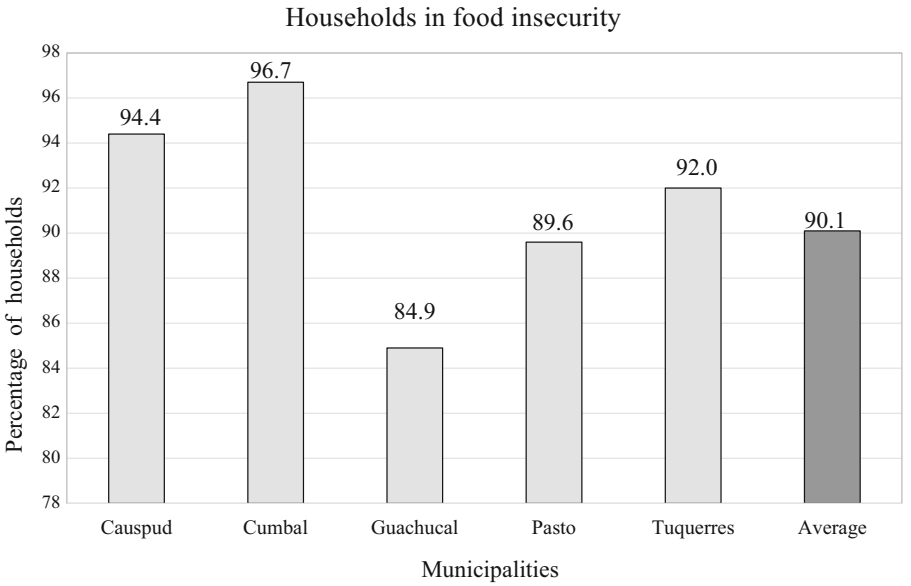

Fig. 2 Percentage of households with food insecurity for the five municipalities under study, located in South Colombia in Nariño province. This data was taken in 2012 by the Project SAN-Nariño. The light-grey columns are the municipalities and the dark-grey column represents the average

cause of anaemia worldwide. Other effects of iron deficiency are decreased capacity for physical work and spontaneous motor activity; additionally, iron is also a key component of the proteins that are in muscle tissues and is critical for the normal development of the central nervous system. Prevention of iron deficiency includes changes in dietary patterns, food fortification and iron supplementation (Olivares and Walter 2003). On the other hand, zinc is an essential mineral found in more than 200 enzymes involved in a wide range of bodily functions. These enzymes play a role in immune function, wound healing and the synthesis of DNA and other proteins. Zinc promotes normal growth and development during childhood and adolescence. Zinc also plays a role in brain development; zinc deficiency can have a negative impact on multiple bodily functions and cause a wide variety of symptoms. It is for these reasons that the micronutrient deficiencies or hidden hunger are crucial limitations for developing countries and it is therefore recommended that families select food with increased iron

Table 1 Percentage of the population with deficiencies intake for calories, proteins, minerals and vitamins for different age groups. These data correspond to five municipalities in the Nariño province in south Colombia

Age groups	Calories	Proteins	Minerals			Vitamins	
			Iron	Zinc	Calcium	A	C
Under 5 years	56.6	15.8	21.8	81.6	50.8	45.7	5.9
From 5 to 12	73.8	33.2	26.1	91.0	92.1	72.5	17.3
Adults	88.0	85.1	42.7	99.8	91.9	87.9	42.7
Total	72.9	41.9	29.0	91.1	82.7	70.4	20.8

Table 2 Nutritional status for children under 5 years old in the Andean region of Nariño. Data derived from anthropometric assessments, shown in percentages

Nutritional situation by anthropometry	Boys	Girls
Stunting	41.6	30.8
Overweight	23.4	44.4
Obesity	18.0	7.0
Global undernutrition	3.1	1.8

(Del Castillo-Matamoros et al. 2014a, b)

and zinc as part of the daily diet. In the case of potato, iron is available because of the high content of vitamin C (Burgos et al. 2007; Love and Pavek 2008). This is an important fact when considering potato as a target crop to improve the FSN.

In addition to these deficiencies, Colombia has increased rates of overweight and obesity. The ENSIN reported that 4.6% of Nariño children aged 1–4 are overweight (ENSIN 2010), and we found the levels for overweight children much higher than the values reported by the national survey of food security and nutrition (Table 2). This strong difference between the data from ENSIN (2010) and our data may be because of the nature of the sample that belonged to an eminently rural population, even when the sample considered urban and rural sectors (Del Castillo-Matamoros et al. 2014a, b). Causes for the high incidence of overweight people are the monotonous diets typically composed of rice and pasta, therefore underscoring the importance of promoting a diverse diet.

The results from Tables 1 and 2 clearly present a severe malnutrition in all age groups that needs an integral strategy to overcome it; therefore, it is crucial to produce more nutritious food.

Nutritional Quality in Potato Tubers and Agronomic Traits

Macro- and Micronutrients in Potato Tubers

The evaluations of nutritional contents in potatoes were conducted in unpeeled and boiled tubers according to the main way of preparation in Colombia. The genotypes were characterized for protein, carbohydrates available, fat, ashes, insoluble fibre, soluble fibre, zinc, iron, calcium, dry matter and phenols (Table 3). The results compare the values obtained for the new potato cultivars with the current yellow commercial cultivar, Criolla Colombia.

Protein content for the new cultivars is highest in Criolla Dorada and Criolla Sua Pa (Peña et al. 2015). Potatoes are not considered an important source of protein; however, its quality has desirable properties because potatoes have a well-balanced amino acid profile (Murniece et al. 2011), which includes lysine, methionine, tryptophan and threonine (Camire et al. 2009).

For fat, our results confirm that the potato is a food that provides low amounts of fat in the diet (Zaheer and Akhtar 2014), and the ash content varied little among genotypes (from 4.3 to 5.1 g per 100 g DW).

Table 3 Macronutrient and micronutrient contents in boiled potatoes with skin of new yellow cultivars and the current yellow commercial cultivar, Criolla Colombia. Values expressed in g per 100 g of dry matter (DM)

Nutritional compounds	New potato cultivars			Commercial cultivar
	Criolla Dorada	Criolla Ocarina	Criolla Sua Pa	Criolla Colombia
Protein	1.8	0.7	1.8	0.8
Carbohydrates available	13.1	20.2	13.9	14.6
Fat	0.1	0.1	0.1	0.0
Ashes	0.9	1.2	1.0	0.9
Insoluble fibre	2.6	1.5	2.2	2.4
Soluble fibre	0.4	0.2	0.9	0.9
Zinc*	0.3	0.3	0.3	0.2
Iron*	0.4	0.5	0.4	0.3
Calcium	2.4	2.6	2.1	3.0
Dry matter	19.0	23.9	19.8	19.1
Phenols—Chlorogenic acid	0.7	3.2	2.6	1.5

*Values in mg/100 g DM

We measured fibre in the advanced breeding clones since the soluble dietary fibre has cholesterol-lowering and hypoglycaemic effects (Laerke et al. 2007) and the insoluble dietary fibre has water absorption and intestinal regulation properties (Oh et al. 2014). In addition, the cultivar Criolla Dorada has interestingly values for dietary fibre.

We did not find any statistically significant differences among the new cultivars for iron content, but all the new cultivars had higher iron content than the control (Criolla Colombia) and the tetraploid potatoes (data not shown). Moreover, zinc content was higher in the new potato cultivars than in the control.

The polyphenol analysis identified four polyphenols compounds: chlorogenic acid, neo-chlorogenic acid, crypto-chlorogenic acid and caffeic acid. Chlorogenic acid was the major representative and varied between 0.77 and 7.98 g kg^{-1} DW (dry weight) followed by crypto-chlorogenic acid (from 0.09 to 1.50 g kg^{-1} DW). These are promising results because chlorogenic acid is reported as a health-promoting compound (Andre et al. 2007b; Kubow et al. 2014; Sadeghi et al. 2016; Gálvez-Santana et al. 2017) and it is present in high concentration in Colombian germplasm and in the more nutritious potatoes (Piñeros-Niño et al. 2016).

The More Nutritious Potatoes' Impact on Iron Accumulation

The clinical experiment followed the Colombian methodology employed by the National Institute for Health in terms of taking the blood samples and the analysis. We found a statistically significant increase of haemoglobin levels, a clinically significant increase of ferritin levels, an increase of average values of weight and height, a greater proportion of appropriate weight for height and a decreased risk of low weight for

height (Bustos 2015). These promising results open the opportunity for the scaling up of these more nutritious potatoes to impact the rural and health sectors in Colombia.

Yield and Resistance to Late Blight in More Nutritious Potatoes

The More Nutritious Potatoes are three yellow cultivars with a high productivity given their yield. They also present higher resistance to late blight in comparison with the cultivar control (Criolla Colombia). The yield obtained in the AETs is shown in Table 4. The more nutritious potatoes substantially exceeded the national yield of these kind of potatoes, from a national average of 12 to 27 t/ha. Therefore, the recommendation for farmers is to reduce the areas cultivated with yellow potatoes and to use the land for other crops, especially vegetables and fruits. This way, the farmers will be able to contribute to the availability of food and they will also be able to regulate the supply of potato in the markets. The productivity of more nutritious potatoes is represented in higher yield and less production costs, not only because these cultivars have better resistance to late blight, but also because farmers substantially improved agricultural practices.

The more nutritious potatoes are also more resistant to late blight. This is a fundamental trait for the potato breeding programme since late blight is the main disease that affects the foliage. Furthermore, without chemical control, the crop can be completely destroyed. Hence, farmers applied fungicides that cause environmental deterioration on a weekly basis. The phenotypical characterization conducted under field conditions indicates that Criolla Dorada is more resistant to late blight than Criolla Ocarina, and Criolla Ocarina is more resistant than Criolla Sua Pa. The selection of these cultivars was based on the field evaluation and this data allowed the researchers to conduct the genetic and metabolomics studies to find molecular markers and metabolites associated with this trait (Yogendra et al. 2014a, b, 2017; Álvarez et al. 2017).

We found two novel associations between SNPs and quantitative resistance to late blight; these associations localized in expressed genes. The first genetic association maps in the gen *StGP28* (Stem 28 kDa glycoprotein) in the locus PGSC0003DMG402016495 and explains 11% of the phenotypic variance. The second association, maps in the gen *StTL15A* (Thylakoid lumenal 15 kDa protein 1) in the locus PGSC0003DMG400034939. These associations explain 11 and 7% of the phenotypic variance, respectively (Álvarez et al. 2017).

The analyses of non-targeted metabolomics showed the differential accumulation of several phenyl-propanoids, polyphenols, fatty acids, flavonoids and benzilisoquinoline alkaloids in resistant plants before and after inoculation with *Phytophthora infestans*, in

Table 4 Average yield of the more nutritious potatoes in the Agronomic Evaluation Trials, presented in the provinces of Nariño and Cundinamarca

Region/province	Average yield (t/ha) of more nutritious potatoes		
	Criolla Dorada	Criolla Ocarina	Criolla Sua Pa
Nariño	37.09	32.81	37.43
Cundinamarca	27.49	21.21	25.78

National yield for yellow potatoes: 12.0 t/ha

comparison to susceptible controls. These metabolites have been associated with cell wall reinforcement and antimicrobial compounds. Gene expression analyses showed a differential expression of enzymes related to these metabolite biosynthetic pathways in resistant plants, especially in response to the pathogen (Yogendra et al. 2014a, b). In addition, functional validation of *StWRKY8* uncovered the importance of this gene as a positive regulator of the benzylisoquinoline alkaloid pathway and resistance to *P. infestans* in potato (Yogendra et al. 2017).

Moving the Knowledge from the Bench to the Field

The active participation of male and female potato growers favoured the inclusion of selection criteria regarding acceptance of the cultivars. Also, their participation in the selection facilitated the adoption of the cultivars and their scaling-up, since through the trials they were able to know their advantages. Moreover, the new cultivars surpassed current commercial cultivar in different aspects that are important for the farmer's judgments. These new cultivars generated new revenues of 18% (Table 5) because their productivity was represented in the higher yield and the lower production.

Farmers participated actively in 22 AETs during 2013–2014. Out of 714 participants in the FFSs, at the end of the research 600 participants completed the entire cycle, with a desertion rate of 16% (Table 6). Ninety-eight percent of the small potato growers that were participating in the FFCSs were planting the more nutritious potatoes and 88% of them pointed out that they were using high-quality potato seeds according to the survey applied to the FFCS's participants. These results interestingly highlight the first stages of the adoption of the new nutritious cultivars among small-scale potato growers. These results additionally underscore the establishment of a system that preserves the quality of these potatoes through the production of high quality seed. The direct work with small potato growers, the training based on building capacities and the participative research are pillars to move research results to the field, all the while benefiting the lower classes.

The Scaling Up of a Sensitive-Nutrition Agriculture Innovation: the More Nutritious Potatoes

The scaling up of a sensitive-nutrition agriculture innovation is a complex process and less is known about how to operationalize the right mix of actions to equitably expand

Table 5 Production cost for yellow potatoes based on a comparison between a current, commercial cultivar (Criolla Guaneña) and a new nutritious cultivar (Criolla Dorada), 2014

Yellow potato cultivars	Yield (t/ha)	US $ /ha*		
		Income	Costs	Benefit
Commercial cultivar, Criolla Guaneña	33.5	13,238	3515	28,196
More nutritious potatoes: Criolla Dorada	37.4	14,804	3330	33,274
Difference	4.0	1566	−185	5078
Total difference				18%

*1 US $ = 2900 Col $

Table 6 Social methodologies and actions implemented for the scaling-up of the more nutritious potatoes

Social methodologies	Participating units	Number of participants	Total participants
Participative selection (2013–2014)	22 Agronomic Evaluation Trials	27 Average	600
Family Farming Community Schools (FFCSs)	1st. Cycle: 8 groups 2nd. Cycle: 6 groups	1st. Cycle: 226 2nd. Cycle: 110	336
Home Gardens for Life	8 groups	160	160
Rural Entrepreneurs Nuclei (REN)	4 Farmers associations	Cooprolac: 32 Asogadan: 18 Asaais: 33 Asopapa: 50	133
Leadership Schools in Sovereignty and Food Security and Nutrition	5 groups	213	213
Strategy for supplementation with Micronutrients in Powder (MNP)	2290 families	2290 families	9160*
Synergies with other projects	4 projects	24,542 people	24,542
			Total: 35,144

*The total number of participants is calculated assuming that the average number of family members in Nariño is four people

the innovation at scale and in different contexts (Gillespie et al. 2015). We proposed a model for the scaling up of More Nutritious Potatoes that implies (1) to reach farmers of different geographic areas to the municipalities where the selection was conducted; (2) to ensure that the small potato growers obtain benefits from this innovation; (3) to establish a good quality potato seed system; (4) to reach consumers and promote good food habits. These four points require collaboration with institutions at the local, regional and national levels to give sustainability to the whole process. They also require a team with specialists from different disciplines such as agricultural production, human nutrition, gender equity, entrepreneurship and rural development. This team works in a transdisciplinary way and understands the complexity of the problem at hand and is in a knowledgeable dialogue with the target communities. It is crucial to respect the culture of each community and to be able to address changes without violence. This is especially important when addressing gender issues.

In Colombia, the production of potatoes with low quality seeds has favoured the spread of pathogens and pest insects (Ministerio del Ambiente 2004). Therefore, it is crucial to train the farmers that are interested in being seed producers for developing the seed production business and to strictly follow the regulations in order to gain credibility and to develop a sustainable process.

The seeds of the more nutritious potatoes are multiplied in partnerships with four farmers' organizations. We selected the four farmers' organizations according to an evaluation that measured the following basic capacities: (i) tradition; (ii) organization; (iii) interest in the topic. Assais (in Nariño) and Asopapa (in Cundinamarca) are organizations that are dedicated exclusively to potato cultivation. This has favoured their training and programme development. The other organizations, Asogadan (in the rural area of Bogota) and Coprolac (Nariño), have interests in dairy production in addition to potato cultivation. Although the training goes according to schedule, the

level of involvement of the associates is lower. It was observed that small-scale potato producers generate a strong commitment to the process of expansion, mainly because they perceive that new cultivars are more productive and have nutritional compounds; moreover, these compounds are promoting healthy lifestyles and are new factors in terms of multiplying these cultivars.

The four organizations are supported in organizational and managerial matters using REN methodology to produce and commercialize high-quality seed potato. It is planned to reach two million consumers in a period of 2 years (Fig. 3). The partner organizations started the multiplication process with mini tubers that are pathogen-free, and from these tubers the process will advance through the following categories. The farmers work with the scientific team in the selection of the plots to multiply the seed potato. Soil samples are evaluated for the pathogens *Rosellinia pepo*, *Spongospora subterranea* and *Globodera pallida*, which are not allowed in the seed potato tubers. The farmers recognize the symptoms and signals of these pathogens and apply this knowledge in the selection of seed potato.

To generate income to the farmers and to the More Nutritious Potatoes programme, the business association will receive an input of seed in the registered category. This way, the farmers can commercialize the multiplication of this seed in the "high-quality seed potato" category and will also be able to obtain revenues for their maintenance and for the seed system, as well. Generating quick revenues is an important financial factor.

We implemented REN as a methodological strategy to produce high quality potato seed and to establish the basis for a public policy. REN's methodology seeks to strengthen business capacity and the autonomy of organizations.

The expansion of more nutritious potatoes reaches the end through the consumers, especially through the educational programme in synergies. Other projects are also present in schools in Bogotá and Cundinamarca, where we reach 22,000 school-age children by directly promoting good food habits. Furthermore, we are also reaching the Colombian population through the participation in the National Campaign for Potato

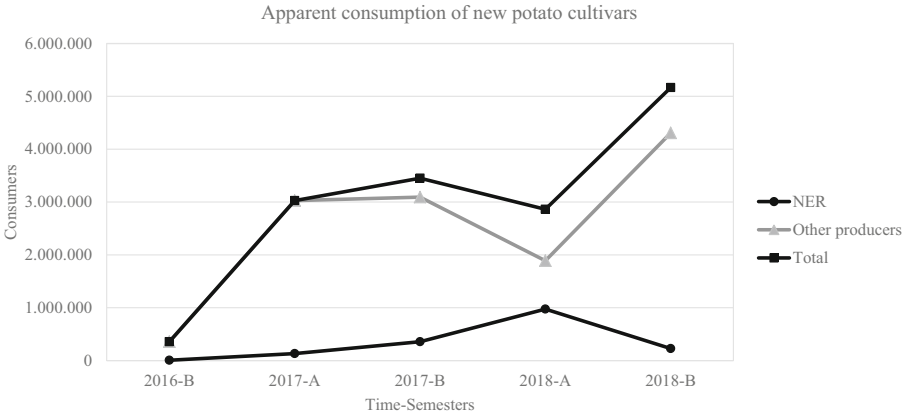

Fig. 3 Consumers of more nutritious potatoes, assuming 21% post-harvest losses, that will be reached by the end of the 2018-B semester. The line with circles represents the consumers that will be reached by Rural Entrepreneurs Nuclei, and the grey line with triangles depicts the consumers that will be reached by other medium- and large-scale potato growers. Lastly, the line with squares shows the total of consumers that will be reached by the more nutritious potatoes

Consumption of the Ministry of Agriculture and Rural Development. This allows us to share our research results and scientific knowledge about nutritional properties of new cultivars of yellow potatoes.

Generating Connections Between Agriculture and Food Security and Nutrition

FFCS seeks social in better, more productive and more profitable cultivars are not sufficient to improve the nutritional status of the population given that income can improve without concurrently leading to the improved well-being and nutritional status of the population (von Braun and Kennedy 1994; World Bank 2007). Evaluations of the State's efforts to achieve significant advances in the FSN solution point to the need to generate connections between sectors, such as Agrarian and Health, and between levels of government and the private and public sectors. There also needs to be a presence of national, departmental and municipal action.

Generating connections between FSN and agriculture demanded a trans-disciplinary team, synergies among the different institutions involved and the proactive involvement of the population on public policies to overcome FSN problems. Incorporating these components has required the use of social methodologies to actively involve the families targeted in this project. At present, a total of 842 community members participates in different social methodologies and 35,144 people are involved in the whole methodology for the scaling-up of the more nutritious potatoes (Table 6), including the synergies done with other projects.

These social methodologies emphasize active participation to tap own resources, highlight women as agents of change and establish activities in close cooperation with government policies in agriculture, health and education, all while facilitating synergies with other national and local projects.

An important result in linking agriculture and nutrition is that the potato breeding programmes in Colombia now consider nutritional quality as one basic criterion for the development of new cultivars. Thus, the new cultivars of potatoes in Colombia will not only be more productive, but more nutritious. For this purpose, information bases were created on the nutritional content and genetics of the different native potatoes of Nariño; thus, in the future they will be able to develop cultivars in less time and in a cost-effective and productive manner that is respectful of the environment.

Education for Social Change

FFCS seeks social development and talent training through a strategy that promotes autonomy in families and communities. It also seeks to impact public policies to develop significant and sustainable change in the living conditions of the communities. FFCS takes advantage of different institutional resources and successfully integrates activities specific to agriculture and FSN, forming a real link between agriculture-nutrition. The FFCS methodology is a powerful social innovation to create a social fabric and facilitate the development of Home Gardens for Life, REN, Leadership Schools in SFSN and the Strategy for Supplementation with Micronutrients in Powder.

The concept of social change in FFCS refers to small changes in individuals and communities that allow meaningful progress to solve the problems of vulnerable families and communities and to advance the development of equal opportunities.

These changes may arise from knowledge, reflections and practices. These changes may also arise through dialogues concerning traditions, which facilitate the understanding of the world and its social groups through the stimulation of democratic values such as tolerance, solidarity, justice and non-violence. Therefore, social change includes changes in gender relations, the promotion of dialogue and consultation to solve conflicts, the valuation of respect, and solidarity and confidence for the construction of social fabric.

FFCS coordinated different institutional resources by developing alliances with municipal mayors, regional authorities, Nariño Health Institute and FAO office in Nariño. The Colombian Institute of Family Welfare incorporated its training programmes for community facilitators, publications and materials developed by the project based on research results, such as the manual, "From the Garden to the Table" (*De la Huerta a la Mesa*) (Del Castillo-Matamoros et al. 2013). This manual promotes healthy behaviours and habits in the daily activities of the home. The manual, "Traditional knowledge on Flavors of the Andean Nariño Communities," (*Sabores y saberes de las comunidades andinas Nariñenses*) was also referenced throughout the course of this investigation (Del Castillo-Matamoros et al. 2014a).

The role of women in the family and in the community is visible, since farmers, women and men not only improved their capacities for agricultural production and selected the best potato cultivars because of their agronomic conditions and culinary characteristics, but also had the opportunity, together, to reflect on the roles that men and women play in the family. This dialogue advanced the recognition of gender inequality. These women and men gained the confidence to express themselves and share their concerns about issues of importance with the community.

Key Findings and Perspectives

This project demonstrates that the combination of scientific knowledge and traditional practices of producers can generate concrete solutions to problems of food insecurity in the short and medium term.

Participatory research in the selection of new cultivars is a strong methodology that contributes to food security because it is a hook for organizing farmers' families to strengthen health programmes. Through the development of a new potato, the incomes of rural families will improve and they will be exposed to cultivars that contain a better nutritional quality.

We present a model for linking agriculture and nutrition that starts with a clear identification of the problem and generates diverse solutions to tackle it from the perspective of agriculture and nutrition. Given its complexity, this kind of initiative needs to be long term in order for it to be applied and for its effects to be seen.

Acknowledgments The authors are very grateful to all the members of the Canadian and Colombian teams and to the communities participating in Nariño, Cundinamarca and Bogotá rural.

Funding Information This research was funded by the International Development Research Centre (IDRC) and Global Affairs Canada, through the Canadian International Food Security Research Fund (CIFSRF), which funded the SAN-Nariño Project and More Nutritious Potatoes Project.

Compliance with Ethical Standards

Ethics Statement All authors have been personally and actively involved in the substantive work leading to the manuscript and will hold themselves jointly and individually responsible for its content. The authors have no conflict of interest.

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