Case-studies on the impact of germplasm collection, conservation, characterization and evaluation (GCCCE) in the CGIAR

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Foreword from SPIA Chair

Background
Although many studies over the years have sought to document the impacts of agricultural research, there remain critical gaps in the extent to which different components of the CGIAR portfolio have been studied. One area of CGIAR research and related activities that many recognize as being under-assessed is 'germplasm collection, conservation, characterization and evaluation' (GCCCE). This is a large area of CGIAR activity: in 2008-2010, approximately 12% of the CGIAR research spending was devoted to this activity. Although cumulative numbers are difficult to calculate, it has been estimated – based on data compiled and reported in earlier CGIAR Financial Reports – that in the years from 1970 to 2010, a total of about US $800 million (in 2002 dollars) has been spent on GCCCE related activities. In spite of this sizeable investment, there have been few studies that have attempted to assess the impact of these GCCCE activities or to quantify the benefits derived.

The aim of this study commissioned by SPIA was to measure and value - to the extent possible - the impacts related to GCCCE related activities by the CGIAR. As past efforts in this sort of assessment have been limited in scope, scale, data and methods, one of the initial objectives of this study was to propose a conceptual framework and set of methods that might be applied in future efforts to estimate these types of impacts. The perspective taken with respect to valuation was derived from the concept of total economic value, which embraces multiple sources of value, although not all of which equally amenable to measurement.

The first component of the study was a methodological survey and scoping study carried out by Melinda Smale and Jean Hanson, both recognized experts in the field, to lead this study. Their report assessed the extent to which quantitative and qualitative evidence existed on the impacts of GCCCE within the CGIAR; identified the limitations of the scope, scale, data and methods used to generate the evidence to-date; and speculated about the potential for using data from the 11 CGIAR genebanks on the amount of germplasm conserved by a) type of material, b) period of acquisition, c) extent of characterization/evaluation, d) direction and extent of flow and, e) type of utilization. While they were optimistic about the potential for the latter, they emphasized that this in itself would require a major effort.

The second component of the study was carried out by another consultant, Jonathan Robinson, and it attempted to explore in more depth the potential for further GCCCE work. Robinson's report examined data availability (identified as a key constraint in the Smale and Hanson study) and the likelihood of access to relevant genetic resources-related information (e.g., pedigree status of widely

adopted improved varieties with specific valued traits drawn from the genebanks). Recommendations were made for several case studies that could be usefully investigated in greater detail from an economics perspective, based on development of preliminary counterfactuals. These cases were selected from numerous examples based on a range of criteria. Most important, the breeding process for the crops should be largely traceable. Robinson explored the issues in some depth and ultimately proposed a set of GCCCE impact case studies having good potential for follow-up and comprehensive documentation.

After extensive correspondence with a number of CCGIAR Center genebank managers and two field visits to Latin America, SPIA commissioned the two case studies presented here[1]. SPIA also recruited CS Srinivasan, an expert on the economics of plant genetic resources, to work alongside Robinson. The explicit aim of this component of the study was to demonstrate proof of concept for the economic value of genebanks and for the impact of GCCCE research, as manifested through input to the process of breeding varieties with specific traits. The two specific cases examined were Kasetsart 50 (KU 50) cassava in Thailand and Cooperation 88 potato in China. These were selected based on their success, and hence should not in any way be taken as representative of the full set of GCCCE activities in the CGIAR.

GCCCE impact studies: Kasetsart 50 cassava in Thailand and Cooperation 88 potato in China
SPIA is pleased with the overall effort undertaken here to document the impact of two specific examples of GCCCE activities in the CGIAR. We note, however, that both cases are related to the benefits derived from the use of genetic resources in plant breeding. These two studies have little to say about the broader role of gene banks in long-term conservation of diversity, nor do they have much to say about the growing value of gene banks as sources of study materials for scientists carrying out relatively upstream research, such as genomics or proteomics.

In the two cases considered here, the value of GCCE activities is derived from direct plant breeding efforts that used gene bank materials to develop successful released varieties. One case comes from CIAT – the development of cassava variety Kasetsart 50, which has been widely adopted in Thailand and Vietnam. The other case comes from CIP – the development of potato variety Cooperation 88 in China. A considerable amount of effort has gone into describing and documenting the impact pathway from activity to outcome, notwithstanding the formidable challenges in doing so.

The story of the development of Kasetsart 50 (KU 50)-- a highly productive hybrid cassava variety developed through active collaboration between CIAT and Kasetsart University in Thailand – is an impressive one. KU 50 is currently grown on over one million hectares in Thailand and Vietnam and has also been adopted in Indonesia, Cambodia and possibly China. The authors estimate the aggregate economic benefits accruing from adoption of KU 50 in Thailand and Vietnam currently at US $ 44 million and US $ 53 million respectively (at adoption levels of about 60% and 75%), and much of this would have translated into a substantial impact on poverty alleviation in Thailand and Vietnam through the producer surpluses accruing to cassava growers. Such an impact, the authors argue, would have been difficult to achieve without the use of CIAT cassava germplasm conserved in its genebank in Colombia (the GCCCE activity under evaluation here), and the input of CIAT expertise in breeding cassava.

The CIP case study is also impressive. The authors estimate that the economic benefits accruing from C88 adoption in China upto 2010 were US $ 350 million and would increase to US $ 465 million per year if an adoption ceiling of 600,000 hectares is reached in 6-8 years. C88 has also stimulated growth in the potato processing industry, as it is suitable for both the table and chipping. Adoption of C88 is believed to be having a substantial impact on poverty, providing economic benefits to the poor estimated at $ US 192 million a year in 2010. The authors argue that such an effective poverty

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[1] A third case study to examine GCCCE activity at CIMMYT related to Russian Wheat Aphid resistance was initially proposed but eventually dropped for lack of adequate data.

alleviation instrument would not have been possible without the use of native potato germplasm conserved at the CIP genebank. Inclusion of CIP genebank material in C88 has broadened the genetic base of potato in China and diminished production risks associated with late blight susceptibility. C88 is currently one of the most widely grown potato varieties in the world and its area is set to increase further.

These are important and impressive impact stories for which credit rightly can be attributed to the CGIAR and its NARS partners. Telling the story, and gathering the data and evidence together has not been easy however. In particular, it has been difficult to separate the contributions of gene banks (and related GCCCE research) from those of breeding programs. Apart from inherent conceptual problems, the authors encountered difficulties related to data availability. It proved difficult to quantify the specific costs of the GCCCE research related to these two cases, and more generally, it proved difficult to identify the the unique contribution of the GCCCE activities to the overall effort. What emerged clearly from both the CIP and CIAT empirical studies was a clear recognition of the difficulty in disentangling the benefits of GCCCE from those of breeding. The benefits measured here are more accurately a measure of overall research impacts, but it would not be accurate to claim them for GCCCE alone. The very large impacts quantified here should be attributed to the entire research enterprise rather than to any particular program or activity.

Disentangling those benefits would require in the first instance a more thorough description of the critical linkage between the specific GCCCE activity/output and the resultant improved variety. Had the institutional memory and data been available at the Centers in both the KU 50 and Coop 88 case studies, it would have been useful to know more about what the CIAT and CIP genebank managers actually did to create value, i.e., providing a fuller description of the "material and expertise" used in the development of KU 50 and Coop 88. The full costs of those GCCCE activities required to generate the key outputs would also have to be estimated to calculate a relevant benefit cost ratio.

A second major challenge that became evident is the establishment of the counterfactual. This is always difficult, but perhaps especially so when trying to consider alternative suppliers of the specific GCCCE outputs or other development pathways in the absence of the GCCCE intervention. If the desired traits had not been found in gene bank materials, what would have happened? Would farmers have used chemical controls for pests instead of resistant varieties? Would they have altered planting dates or farming practices? Could breeders have found other sources of the desired traits? While the authors describe a counterfactual in both cases, it is difficult or impossible to know if this is the most appropriate counterfactual.

The methodological and intellectual challenges faced in these case studies are typical of the problems that confront SPIA in much impact assessment work. We typically face difficulties of attribution (linking benefits to specific research investments) and in the development of counterfactuals (understanding what would have happened in the absence of research investments). The current case studies have made valiant efforts to address these issues, and we applaud the authors' frank discussion of the difficulties. Notwithstanding these particular challenges, these studies represent a useful step forward along a difficult path – namely, estimating the economic benefits of GCCCE activities. We believe that these studies have advanced the state of knowledge and have also laid a strong foundation for future research.

Doug Gollin
SPIA Chair, August 2013

Case study 1 - Kasetsart 50 (KU 50) cassava

Summary

Kasetsart 50 (KU 50) is a highly productive hybrid cassava variety developed through active collaboration between CIAT (Centro Internacional de Agricultura Tropical), the Department of Agriculture of Thailand and Kasetsart University in Thailand. KU 50 is currently grown on over one million hectares in Thailand and Vietnam (where it is known as KM 94) and has also been adopted in Indonesia, Cambodia and possibly China. It was developed to escape the potential problems associated with the extremely narrow genetic base of established cassava varieties in Thailand, such as Rayong 1, which dominated for several decades and which represented a threat to sustainable production. In addition to being highly productive in its own right, KU 50 has also been successfully used as a parent in crosses that have produced several hybrid cultivars that are currently being adopted in S.E. Asia. KU 50's pedigree contains germplasm from the CIAT genebank and old introductions into Thailand from neighbouring countries. KU 50 represents a selection from hybrid seed produced from a cross made between Rayong 1 and Rayong 90, the latter of which was the product of a cross between CMC 76 and V 43. CMC 76 represents a key parent in the pedigree of KU 50. It came from the CIAT genebank (collected in Venezuela) and was selected by CIAT cassava breeders during genebank evaluations. V 43 was an old introduction into Thailand from the Virgin Islands. Large programmes of evaluation and selection were conducted over about thirty years at many sites in Colombia and Thailand, which led to the production of KU 50 and other high-yielding hybrid cassava varieties. It is estimated that the aggregate economic benefits accruing from adoption of KU 50 in Thailand (released in 1992) and Vietnam (released in 1995) currently exceed US $ 44 million and US $ 53 million respectively (at adoption levels of about 60% and 75%). In the absence of data, it is not possible to estimate the substantial benefits accruing to downstream users (industrial processors). However, KU 50 has had a substantial impact on poverty alleviation in Thailand and Vietnam through the producer surpluses accruing to cassava growers. It is suggested that such an impact would have been very difficult to achieve without the use of CIAT cassava germplasm conserved in its genebank in Colombia, and the input of CIAT expertise in breeding cassava. The obstacle of a narrow genetic base in cassava varieties grown in S.E. Asia has been overcome and it is expected that greater use of the CIAT genebank germplasm, and increased evaluation of genebank materials, will be made in the future to maintain the momentum established through the CIAT-Thai cooperative venture initiated in 1983.

Cassava

Cassava (*Manihot esculenta*) and all other species of the genus *Manihot* are native to tropical America. Cultivation of cassava is believed to be ancient, but its origin as a crop is unknown. It was introduced into S.E. Asia during the 1800s and became successful during famine years when rice and maize crops failed. Although cassava breeding began in Indonesia in 1908, based on the importation of South American germplasm, S.E. Asia largely relied on simple selections from a relatively limited genetic base. Cassava is a vegetatively propagated, perennial crop and there is no strict harvest season for it. It is grown for its starchy storage roots, but its leaves are also harvested as a vegetable. World production of cassava in 2010 was 228 million tonnes from a cultivated area of over 18 million hectares (FAOSTAT). The major cassava producers are Africa, Asia and South America, which account for 53%, 33% and 14% of global production respectively. Cassava is a principal carbohydrate source for more than 500 million people worldwide and ranks sixth among crops in terms of calorific contribution. Resource-poor farmers frequently grow cassava as a food security crop. Cassava is used extensively for animal feed and for production of industrial starch. It is also used in bioethanol production, the food and paper industry, plywood production and in the production of monosodium glutamate.

Cassava has received relatively little attention from plant breeders because of its long cycle (18-24 months), which complicates evaluation, and technical problems associated with artificial crossing to produce hybrids.

Cassava production in Thailand and Vietnam

Thailand and Vietnam are the two leading cassava producers in Asia. Thailand is the world's fifth largest producer, producing 22 million tonnes in 2010 (10% global share) and Vietnam is the ninth largest producer, producing 12.8 million tonnes (6% global share). Cassava is the third most important crop after rice and rubber in Thailand and is the sixth most important crop in Vietnam. The Thai cassava industry is the second largest in the world, with output valued at US $ 3.14 billion in 2009. The output of the cassava industry in Vietnam was valued at US $ 893 million in 2009. Thailand is the world's largest exporter of cassava, accounting for over 70% of global exports of dried cassava and 90% of cassava starch.

The trends in production and area devoted to cassava in Thailand and Vietnam since the mid-1980s are shown in Figures 1.1 and 1.2 respectively. Figure 1.3 shows the trends in average yield per hectare in Thailand and Vietnam during the same period in comparison with world yields.

Figure 1.1: Trends in cassava area and production in Thailand (1985-2010).
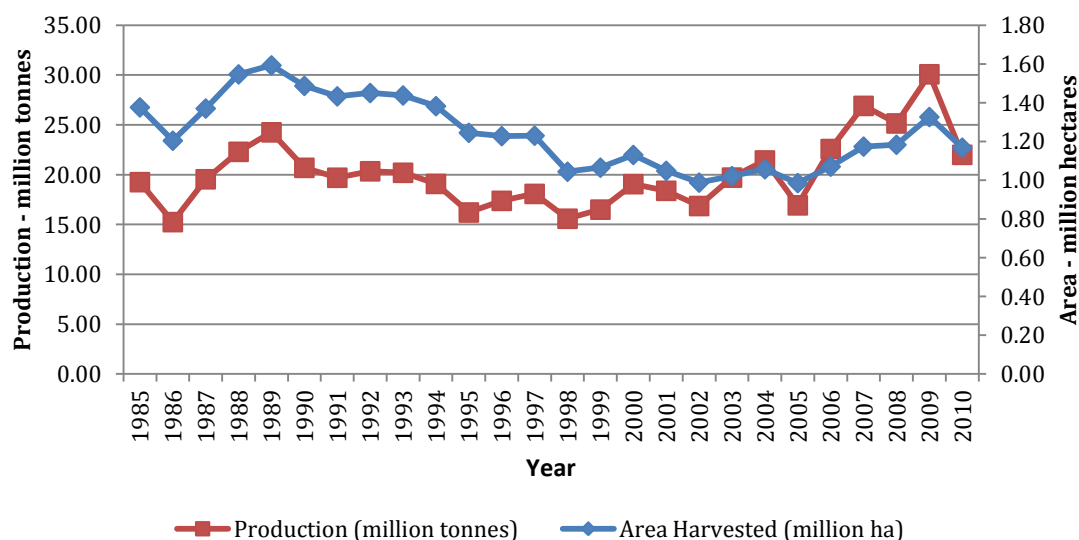
Figure 1.2: Trends in cassava area and production in Vietnam (1985-2010).
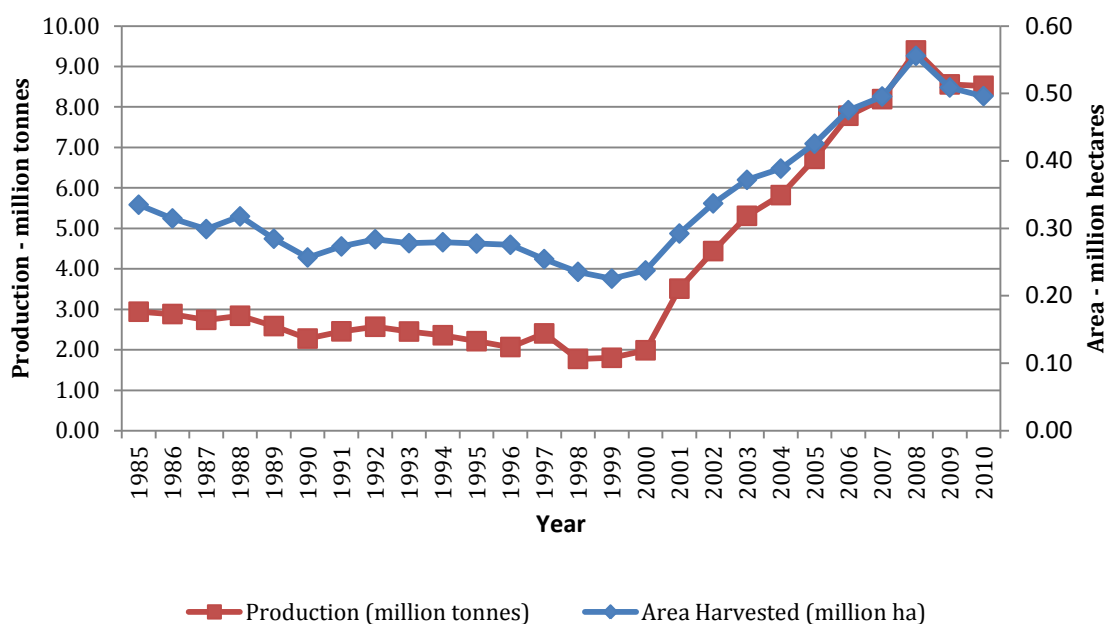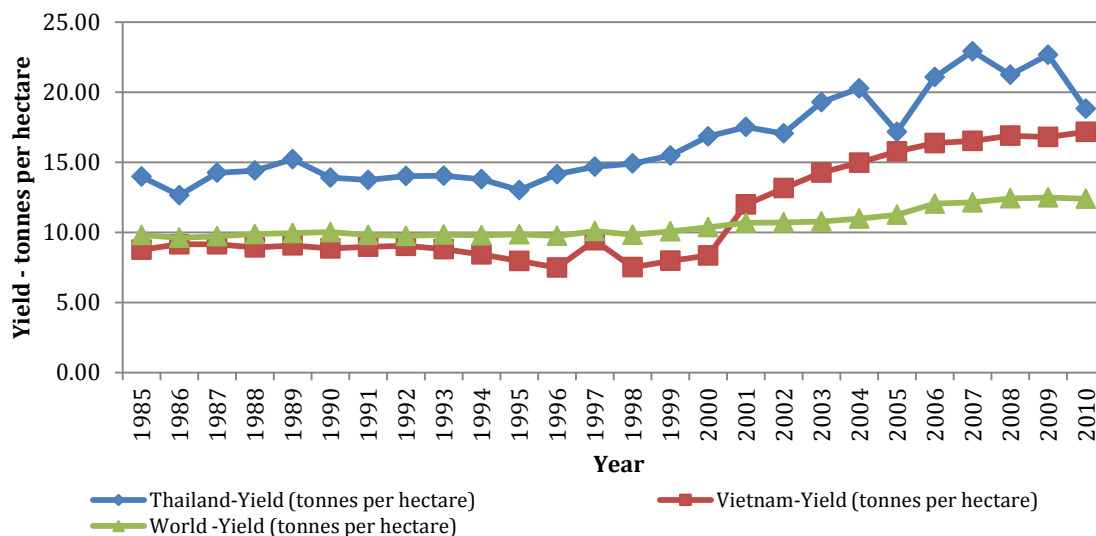

Figure 1.3: Trends in cassava yields in Thailand and Vietnam over time.

From the mid-1980s to the mid-1990s, cassava yields in Thailand and Vietnam were stagnant and the area under cassava was in decline. The decline in cassava area was associated with its image as a crop with adverse environmental impacts – particularly soil erosion and degradation at higher elevations. The development and adoption of new varieties, including Kasetsart 50 (KU 50), appears to have contributed to reversing the yield decline and resumption of area expansion. Ideally, the economic impact of KU 50 (and other new varieties introduced since the 1980s) should be assessed not only in terms of yield gain but also in terms of the mitigation/arrest of environmental damage previously associated with cassava cultivation in those countries.

Cassava yields in Thailand, which were always above average world yields, have shown a steady upward trend since the mid- 1990s, reaching a level of 22.68 t ha^{-1} in 2009, 81% higher than world yields. Yield increases in Vietnam have been much more dramatic – yields that were previously below the world average have shown a sharp upward trend and were 17.18 t ha^{-1} in 2010, 38% above world yields. The growth in yields since the mid-1990s has been the principal driver of growth in production, which has not seen significant area expansion (Figure 1.1). In Vietnam, although the area under cassava doubled in the period 1995-2010, production increased four-fold over the same period owing to yield gains.

The CIAT-Thailand cooperative breeding programme

CIAT's (Centro Internacional de Agricultura Tropical) cassava programme began in the 1970s with the aim of extending the successes of the Green Revolution beyond small-grain cereals and the farmers growing them. The initial decade of CIAT's programme was dedicated to collection of germplasm and development of germplasm suitable for breeding advanced clones. Emphasis was placed on i) collecting a broad range of genetic variation from the centre of origin and diversification of cassava, ii) evaluating material under a range of conditions, iii) improving tuber yield and the components of yield.

Cassava breeding in Thailand had begun 1937 with the introduction of 20 cultivars from Malaysia and the Philippines. Between 1963 and 1977 65 more cultivars were introduced from the Virgin Islands and Colombia. A collaborative breeding programme was established between the Thai Department of Agriculture and CIAT in 1983 with the aim of producing replacement varieties to Rayong 1. Rayong 1 had been used in open-pollinated breeding previously, but without substantial success. Controlled hybridization with Rayong 1 began in 1975 (Kawano, 2003). CIAT introduced advanced hybrid CIAT/Thai cassavas into Vietnam from 1989.

Several improved hybrid cassava varieties were released in Thailand during the 1980s and 1990s, but none were superior to Rayong 1. Between 1994 and 1998 several additional varieties were produced, multiplied and distributed to farmers, including Rayong 90, which was released in 1991. KU 50 (its name reflects the cooperation of CIAT with Kasetsart University in Thailand – where its early stage selection was conducted), is a product of a cross between Rayong 1 and Rayong 90, and represents a major advance in development of a cassava hybrid adapted to S.E. Asian environments.

The Thai Tapioca Development Institute Foundation (TDDI) multiplied and distributed KU 50. KU 50 has spread into Cambodia, where it is probably known by different names. KU 50 is also suited to some Chinese environments and is grown in Indonesia, where it has apparently retained its name. KU 50 has been used as a parent in crosses with Rayong 60 (released in 1987) to produce Huay Bong 60 (released in 2003) and Huay Bong 90 (released in 2008), both varieties being very productive.

The breeding scheme and origins of the germplasm

KU 50 has a relatively straightforward pedigree, as indicated in Figure 1.4 below, but its simplicity belies the extensive collection, evaluation and breeding work that contributed to its development.

Figure 1.4: The pedigree of KU 50.
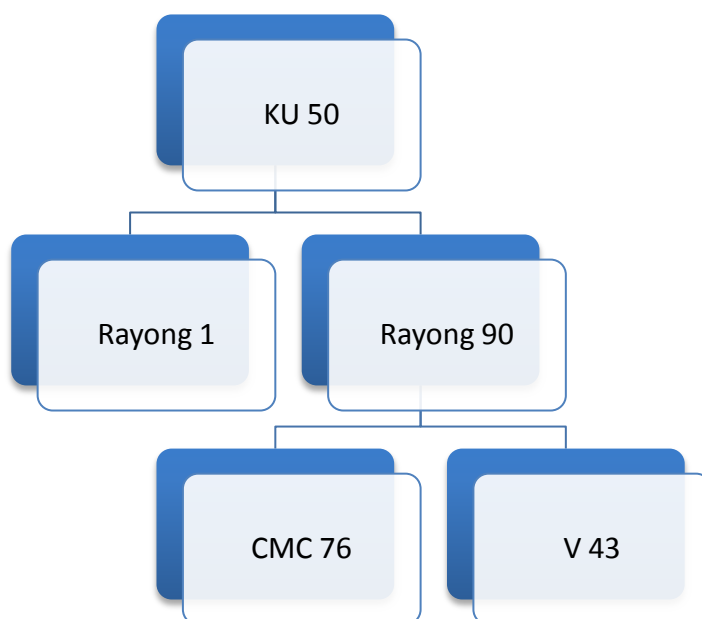
Rayong 1 is an old Thai landrace cassava (possibly from Malaysia) that was grown extensively in Thailand (and was the most widely grown cassava in the world - over one million hectares in Thailand at its peak) from the 1960s to the 1980s, although it was only given its official name in 1975.

KU 50 was selected from hybrid seeds produced from a cross made at RAY-FCRC (Rayong Field Crops Centre of the Department of Agriculture) in Thailand between the improved variety Rayong 90 (released in 1991)[2] and Rayong 1. Rayong 90 was a product of a cross made in 1978 between two cassava lines, V 43 (male) and CMC 76 (female), respectively collected from the Virgin Islands and Venezuela. CMC 76 was received in Colombia in 1970 and is listed in the CIAT genebank as accession COL 1505. It was collected in Venezuela on 01.08.67. V 43 was one of several clones introduced into Thailand from the Virgin Islands in 1965 and appears not to be included in the CIAT collection. KU 50 was released in Thailand in 1992 and later (in 1995) was released in Vietnam as KM 94. The primary feature of KU 50 that makes it preferred is its high dry matter/starch content. It must be emphasized that the success of KU 50 is largely due to the use of CMC 76, which was identified by CIAT as a good prospective parent after intensive evaluation.

Collection, evaluation and breeding
The CIAT genebank maintains conserved cassava germplasm for distribution to interested breeders and researchers. It also manages associated data, including the standard characterization data that detail origin, date of entry, synonyms etc. and evaluation data on useful traits, such as resistances. The breeders and researchers evaluate the germplasm for useful traits in a range of environments. Evaluation is a continuous process as breeders look to improve their breeding material. Cassava is relatively little bred crop, but there is a need to improve many features that contribute to enhanced yields and the germplasm is thus evaluated for many traits. In the case of the CIAT-Thai programme, much of the work was carried out in Thailand (where the environment is very different to that in Colombia).

CIAT's cassava collection derived from systematic collections begun in 1971 in Colombia, which were subsequently extended to Venezuela, Ecuador, Mexico, Panama, Brazil, Costa Rica, Puerto Rico and Peru. Most accessions were collected from farmers' fields, but some came from national collections. CMC 76 was collected in Venezuela on 01.08.67 and the CIAT genebank got it as accession COL 1505 in 1970. V 43 originated from the Virgin Islands and entered Thailand in 1965. It is not possible to cost the collection and conservation activities for the respective parents of KU 50 accurately, but CMC 76 was only one of numerous accessions collected in Venezuela more than 40 years ago and the information relating to V 43 is simply not available.

In 1973 CIAT began a comprehensive field evaluation of its 2218 clonal accessions. By the 1990s the collection had grown to >5000 accessions from 23 countries, and the evaluation continued. The Cassava Programme managed the genebank during the early days of CIAT and it was not until the mid-1980s, when *in vitro* techniques were developed, that the genebank became jointly managed by the Cassava Programme (field collection) and the Genetic Resources Unit (the *in vitro* collection). By the mid-1990s the field genebank was dispensed with and the entire cassava collection was held only *in vitro*, and became fully managed by the Genetic Resources Unit. A cassava breeder identified CMC 76 as a landrace variety with traits of potential value for Asia during the course of genebank evaluations. The traits being sought at that time were specifically adaptation to seasonally dry growing conditions, high yield potential, erect plant type, and high, stable starch content.

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[2] Rayong 90 was widely distributed to Thai farmers by the Thai ministries of Extension and Cooperative Promotion between 1994 and 2001. In 2006 Rayong 90 occupied 119, 000 ha (11% of the total area) while KU 50 occupied > 630,000 ha (>57% of the total). Respective production figures were 2,479 t and 12,940 t (Rojanaridpiched et al., 2008). It would be possible to include data for Rayong 90 in calculations of economic benefits and poverty alleviation as it was a product of the breeding programme that produced KU 50. However, there would also be a case for including benefits derived from using KU 50 as a parent in more recent crosses. Ultimately this would lead to calculating the benefits for an entire breeding programme. It is therefore considered prudent to restrict economic benefit calculations solely to those for KU 50, acknowledging that the programme generated benefits beyond those attributable to adoption of KU 50.

Three evaluation sites were chosen in Colombia according to soil type, soil fertility, rainfall and important biotic and abiotic stresses. The evaluation scheme involved seedling trials in pots, single-row field trails and replicated yield trials (see Kawano, 2003 for details). Selected genotypes were then hybridized, the products of which were then evaluated. Between 40,000 and 60,000 F1 seeds were produced from 200 to 400 parental combinations annually.

Following production of advanced hybrid populations, further selections were made and evaluated in different environments. A cycle of selection-breeding-evaluation operated on an annual basis in a programme of large-scale recurrent mass selection. On average 30,000 seeds were sown in seedling trials, 3000 were selected for single row trials following evaluation, and 500 were selected for replicated yield trials in Colombia (at the three sites).

The breeding programme in Thailand (begun in 1971) was based on open-pollination using Rayong 1 as a parent, but it did not produce any commercial cultivars. Controlled hybridization followed in 1975 using Rayong 1 and a small number of CIAT clones. The selections were based on breeders' knowledge of the germplasm. More CIAT seed introductions followed. A large-scale breeding and selection scheme was developed at the Rayong Field Crop Research Center, Department of Agriculture, Thailand, in which CIAT began to participate directly in 1983. Each year seven to nine selected clones planted in replicated yield trails were incorporated into the hybridization scheme. Rayong 1 was used as a control (for yield comparison) in every yield trial in Thailand.

Selection and evaluation were conducted at six sites in Thailand that differed in edaphic and climatic conditions, such that all cassava-growing areas of Thailand were represented. A similar selection-breeding-evaluation scheme was set up as was already operating in Colombia, with seedling trials, single-row trials, preliminary yield trials, advanced yield trials and regional yield trials.

It is this large-scale scheme, conducted in Colombia and Thailand, using a vast range of germplasm and breeding expertise that has been responsible for producing KU 50 and all other commercial hybrid cassavas in Thailand (and some elsewhere in S.E. Asia) over the past 30 years. It would be difficult to quantify in terms of costs, but the results are very apparent.

Adoption of KU 50 in Thailand and Vietnam
KU 50 was introduced into Thailand in 1992 and into Vietnam in 1995 (as KM 94). Continuous time series data on the adoption and area share of KU 50 are not available, but a number of point estimates are available for Thailand and Vietnam from various sources (FAO, 2000; TTDI, 2006; Rojanaridpiched et al., 2008; Kim et al., 2008). In Thailand KU 50 is estimated to have reached an area share of 57.15% of the total cassava area by 2006, being planted on over 633,700 hectares (TTDI, 2006). Estimates made by Kim et al. (2008) indicate that KM 94 was planted on over 400,000 hectares in Vietnam by 2008, accounting for an area share of 75.14%. A profile of adoption of KU 50 in Thailand, and KM 94 in Vietnam, is presented in Figures 1.5 and 1.6 respectively. The profiles are based on fitting a logistic curve to the point estimates of adoption using a conservative adoption ceiling. For Vietnam, the adoption ceiling has been assumed to be 80%, as the current area share of KM 94 (75.14%) is already very high and is not likely to increase significantly as new varieties such as KM 140 and KM 98-5, released in 2007 and 2009 respectively, appear to be outperforming KM 94 in terms of yields. For Thailand, an adoption ceiling of 60% has been assumed. Although KU 50 is still among the highest yielding varieties in Thailand, it has strong competition from varieties like Rayong 90 and Huay Bong 60 and 80 and newer releases may soon outperform KU 50 in yields, which will restrict further expansion of area under KU 50. We use this adoption profile to estimate the build-up of economic surplus over time as a result of the adoption of the variety in Thailand and Vietnam.

Figure 1.5: Adoption profile of KU 50 in Thailand.
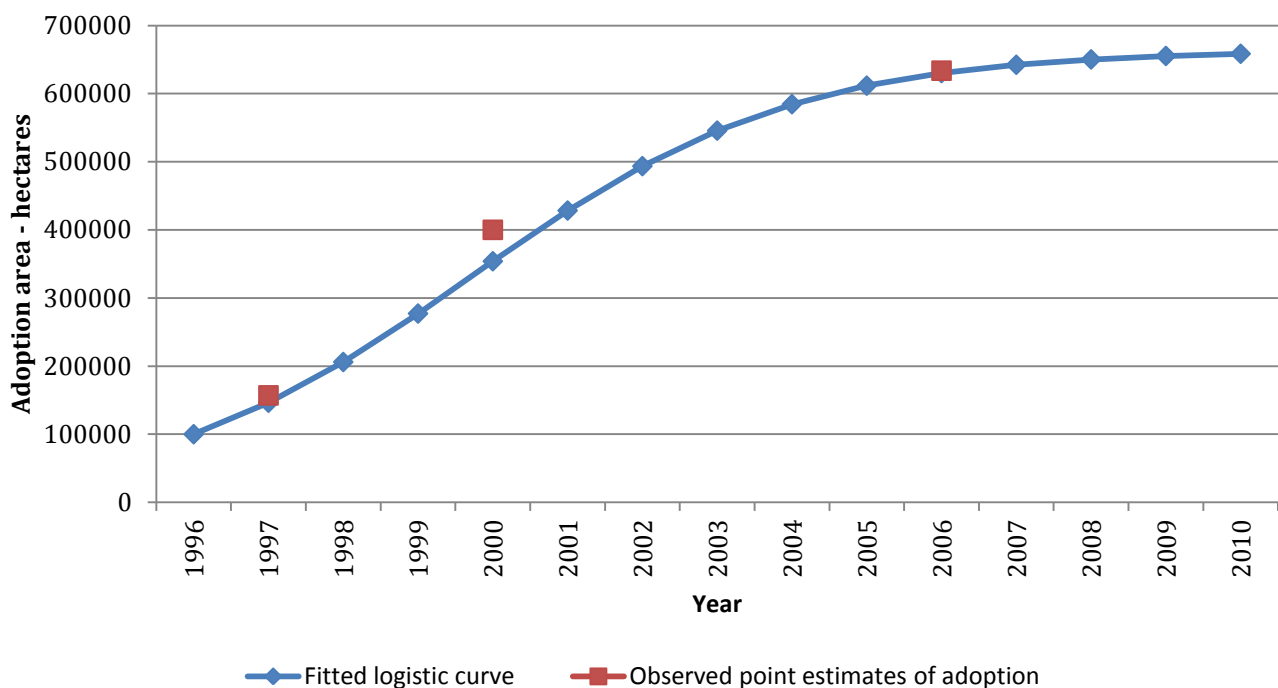
Figure 1.6: Adoption profile of KM 94 (KU 50) in Vietnam.
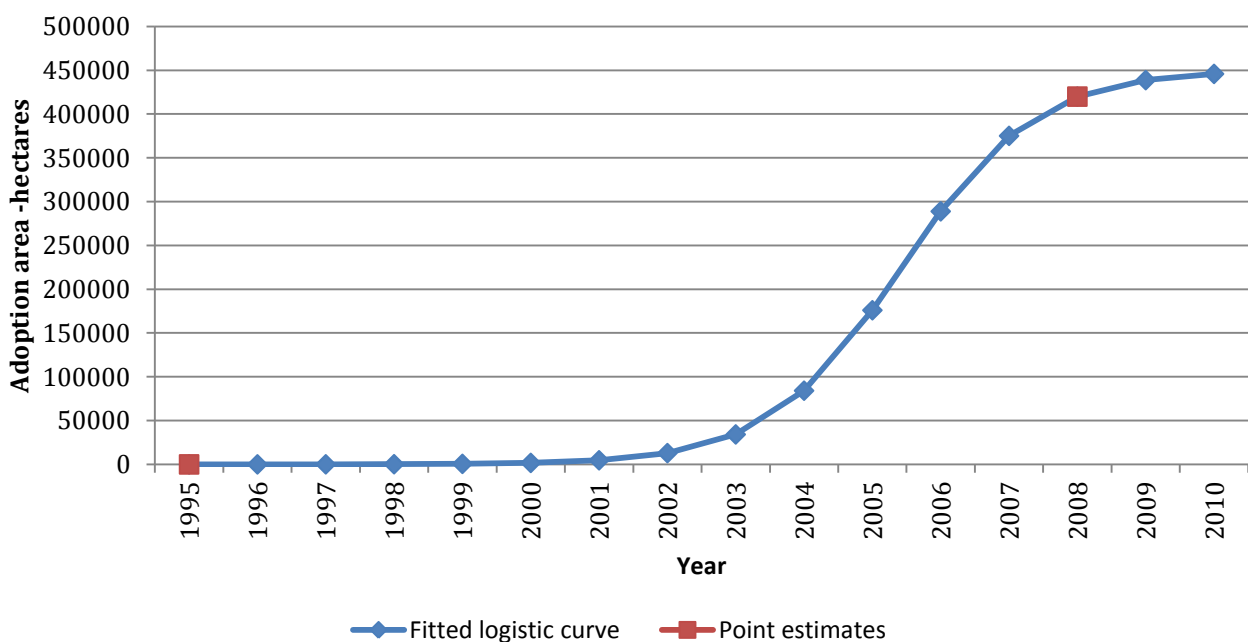
Yield advantage of KU 50 (and KM 94)
In assessing the yield advantage offered by KU 50, the appropriate variety for comparison in Thailand is Rayong 1, which at one time accounted for nearly 100% of the area in Thailand (rendering the entire national production very vulnerable to pests and diseases). The data on the yield advantage of KU 50 over Rayong 1 in agronomic trials over the period 1987-1991 are presented in Table 1.1.

Table 1.1: Yield advantage of KU 50 over Rayong 1 in agronomic trials (1987-1991) in Thailand.

Characteristic	KU 50	Rayong 1	Advantage over Rayong 1
Fresh root yield (t ha^{-1})	28.30	23.11	22.5%
Dry root yield (t ha^{-1})	9.82	7.23	35.8%
Starch content (%)	21.92	17.08	28.3%

(Source: TTDI, 2006)

Data on the yield of KU 50 in cultivation in relation to other important varieties and the national average yields are presented in Table 1.2.

Table 1.2: Comparative yield of KU 50 in Thailand.

Year	Average national cassava yield (t ha^{-1})	Yield of KU 50 (t ha^{-1})	Yields of other important varieties (t ha^{-1})	
1992	14.03	NA	NA	
2002	17.07	17.36	Rayong 1 Rayong 3 Rayong 5 Rayong 60 Rayong 90	13.67 17.91 15.38 18.68 17.44
2006	21.09	21.20	Rayong 1 Rayong 3 Rayong 5 Rayong 60 Rayong 90 Huay Bong 60 Sriracha 1	17.20 20.30 21.80 20.20 21.60 19.60 19.00

(Source: National yields from FAOSTAT (2011), figures for 2002 from Agrifood Consulting International (2004) and figures for 2006 from TTDI (2006))

Data in Table 1.2 demonstrate that the yields of all varieties have shown an upward trend over time, possibly as a result of the adoption of improved management practices by farmers. Although the yields of KU 50 in cultivation have been expectedly lower than yields in agronomic trials, the variety has consistently shown a yield advantage of nearly 4 t ha^{-1} over Rayong 1, the dominant variety that KU 50 replaced. This yield advantage in combination with its adoption over large areas in Thailand has made a significant contribution to the reversal of the yield decline observed in Thailand up to the mid-1990s.

In Vietnam, before 1985, the most popular cassava varieties grown were Gon, H 34 and Xanh Vinh Phu. During the period of 1986–1993, three cassava varieties, HL 20, HL 23 and HL 24, were selected from local cassava collections and released by Hung Loc Agricultural Research Center (HARC). In 1994 they were grown on about 70,000 ha in South Vietnam (Tran Ngoc Ngoan et al., 1995). During the period 1991-2009, the Vietnam Cassava Programme, in collaboration with CIAT, developed and disseminated 7 new high yielding varieties – KM 60, KM 94, SM 937-26, KM 95, KM 98-1, KM 98-5, KM 140 and KM 98-7. KM 60 (1993) and KM 94 (1994/95) were the earliest varieties released through

the collaborative programme with CIAT. These varieties replaced the dominant HL varieties. It would therefore be appropriate to assess the yield advantage of KM 94 in relation to the yield of the HL varieties. Data on the yield advantage of KM 94 from the Regional Yield Trials conducted by HARC in southern and central Vietnam in 1997-98 are presented in Table 1.3.

Table 1.3: Yield advantage of KM 94 from Regional Yield Trials of HARC (1997-98).

Variety	Fresh root yield (t ha^{-1})	Root starch content (%)	Yield advantage over HL 23 (%)	Yield advantage over Xanh Vin Phu (%)*
KM 94	39.6	28.9	67	134
KM 98-1	38.4	27.8	62	127
KM 60	30.2	27.4	27	78
HL 23	23.7	25.4	-	40

*Based on a yield of 16.89 t ha^{-1} for Xanh Vin Phu from farmer plot trials in 1998.
(Source: Kim, H. et al., 2000)

In experimental trials, KM 94 demonstrated a yield advantage of nearly 16 t ha^{-1} over HL 23 (the only HL variety still being cultivated on around 1.08% of the cassava area). The yield advantage in farmers' fields has expectedly been lower, but is still very impressive. An assessment of the yield advantage of the new currently cultivated varieties of cassava developed in collaboration with CIAT over HL 23 is presented in Table 1.4.

Table 1.4: Yield advantage of new cassava varieties over HL 23 in cultivation in five provinces.

Year	Increases in yield and starch content vs. HL 23	
	Fresh root yield (t ha^{-1})	Root starch content (%)
1994	+8.0	+2.5
1995	+9.5	+3.0
1996	+10.3	+3.3
1997	+9.6	+2.9
1998	+10.5	+3.0
1999	+9.8	+3.2

Note: KM 94 yields reported to be around 22-24 t ha^{-1}

(Source: Kim et al., 2000)

These figures suggest that the yield advantage of KM 94 in cultivation would be of the order of 8 t ha^{-1} in relation to the dominant varieties that it replaced. Data on the average yields of varieties in cultivation in 2009 are presented in Table 1.5.

Table 1.5: Yields of major cassava varieties cultivated in Vietnam in 2008.

Variety	Area share (%)	Yield (t ha^{-1})
KM 94	75.54	16.9
KM 140	5.40	20.0
KM 98-5	4.50	20.6
KM 98-1	3.24	20.3
SM 937-26	2.70	19.8
KM 98-7	1.44	17.0
HL 23	1.08	13.5
XVP	2.70	12.0
Others	3.42	6.5

(Source: Kim et al., 2008)

The enormous expansion in area under KM 94 appears to have led to a decline in average yields in relation to yields that were obtained in the late 1990s. This may possibly be the result of the extension of cultivation of the variety to more marginal environments. The data presented in Table 1.5 also show that KM 94 is now being outperformed by many varieties developed through the collaborative programme with CIAT, some of which have KM 94 parentage. However, in spite of the extension of cultivation to over 75% of the cassava area in Vietnam, KM 94 still maintains a yield advantage of nearly 4 t ha^{-1} over HL 23 and nearly 5 t ha^{-1} over XVP.

Estimation of economic surplus from KU 50/KM 94 adoption
The standard approaches to the assessment of economic surplus impacts following the adoption of innovations involve the following steps:

(a) Calculating a supply shift (K-shift) representing the unit cost reduction associated with the use of a new technology on account of yield increase and changes in the cost of production.
(b) Gathering information on expected adoption rates and their evolution over time.
(c) Combining the above information with market information on supply and demand elasticities and equilibrium prices and quantities (Alston et al., 1995).

The formulae used for calculation of economic surplus from adoption of a new variety and the approximations used are described in Appendix-1. The parameters used for estimation of the economic surplus in Thailand and Vietnam are summarized in Table 1.6.

Table 1.6: Parameters for economic surplus estimation.

Parameter	Thailand	Vietnam
Base year for analysis	1992	1995
Cassava production in base year (million tonnes)	20.36	2.21
Producer prices in base year (US $ t^{-1})	30.3	30.2
Base year yields (t ha^{-1})	14.02	7.97
Yield advantage for KU-50/KM-94 (t ha^{-1})	4	8
Yield of KU 50/KM 94 assumed for assessing increase in yields (t ha^{-1})	18.02	15.97
Yield increase due to adoption of KU 50/KM 94 (%)	28.7	103
Increase in cost per hectare associated with adoption of KU 50/KM 94 (%)	17.5	38

KU 50 was introduced into Thailand in 1992 while KM 94 was introduced in 1995 into Vietnam. The year of introduction of the variety has been taken as the base year for the economic surplus

calculations[3]. The quantity of cassava produced and the yield in the base years were taken from FAOSTAT data. Producer prices in the base year for Thailand were taken from FAOSTAT data, while producer prices in Vietnam are based on Kim et al. (2000). For economic surplus calculations, we need the difference between the yield of KU-50/KM 94 and the average yield of other varieties in the base year and in subsequent years, which are not available. Therefore, for assessment of the yield increase as a result of adoption of KU 50 (KM 94) we have taken a yield of 18.02 t ha^{-1} for KU 50 in Thailand and 15.97 t ha^{-1} in Vietnam. The yield increase used in the economic surplus calculations – 28.7% for Thailand and 103% for Vietnam - are based on the yield advantage figures of 4 t ha^{-1} for Thailand and 8 t ha^{-1} for Vietnam discussed in the previous section. No data are available for assessing the increased cost of production associated with the adoption of the new cultivars. The adoption of a new variety need not necessarily entail increased input costs per hectare – although there may be some increase on account of the procurement of improved planting material and greater use of fertilizers. Harvesting and transport costs are likely to go up proportionally with the increase in yield. An assessment of the production costs of cassava in Thailand (FAO, 2006) showed that between 1991/92 (when KU 50 was introduced) and 1997, the production costs of cassava increased from 8,586 baht ha^{-1} to 10,090 baht ha^{-1} - an increase of 17.5%. While this increase may not be entirely attributable to the adoption of new varieties, we have used this figure as an approximation of the increase in costs associated with the adoption of KU 50. In Vietnam, a comparative assessment of the cost of an old cultivar (HL 20) with a new cultivar (KM 60) in 1995-96 showed that the adoption of a new cultivar would lead to an increase in production costs of nearly 38%, principally on account of increased harvesting and transportation costs, higher costs of planting material and enhanced application of fertilizers (FAO, 2006).

Based on the above parameters and the adoption profile of KU 50 estimated previously, the estimates of aggregate economic surplus on account of adoption of KU 50 in Thailand are presented in Table 7.

Table 1.7: Aggregate economic surplus for adoption of KU 50 in Thailand.

Year	1996	1998	1999	2000	2001	2002	2004	2005	2006	2007	2008	2009	2010
Projected adoption profile - % area under KU-50	9.0	18.6	25.0	31.9	38.6	44.5	52.7	55.2	56.8	57.9	58.6	59.1	59.4
Projected area under KU 50 (million ha)	0.10	0.21	0.28	0.35	0.43	0.49	0.58	0.61	0.63	0.64	0.65	0.66	0.66
Aggregate economic surplus (million 1992 US $)	6.7	13.8	18.5	23.7	28.7	33.0	39.1	40.9	42.2	43.0	43.5	43.8	44.1
NPV of economic surplus flow from 1992-2010 (base year 1992 and discount rate of 5%) = US $243.63 million													

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[3] Economic surplus estimations generally incorporate assumptions regarding the autonomous growth of supply (e.g., due to area expansion, increased productivity due to factors unrelated to new variety/technology adoption, such as improvement in infrastructure, management practices etc) so that the benefits accruing on account of the adoption of the new variety or technology can be distinguished from the benefits accruing on account of factors unrelated to research. In the case of cassava in Thailand and Vietnam area and yields were stagnant or declining prior to the introduction of new varieties developed through collaborative programs with CIAT. The new varieties may have reversed the decline in cassava area and facilitated subsequent area expansion. Therefore, in our analysis we have not assumed any autonomous increase in supply in the absence of the new varieties.

The aggregate economic surplus for the adoption of KU 50 was US $ 6.7 million in 1996 when the adoption area was 9%. It is estimated to reach US $44.1 million per year when the adoption ceiling of 60% is reached. Over the period 1992-2010, the net present value of the economic surplus generated by KU 50 with a discount rate of 5% is US $ 243.63 million. The annual economic surplus will decline as and when KU 50 is replaced by other newer varieties. It should be noted that these figures relate to the producer surplus attributable to the variety innovation alone. They do not include the surpluses that may be appropriated by downstream (industrial) users of cassava.

The aggregate economic surplus estimates for Vietnam are presented in Table 1.8 from the year 2000 onwards (reliable adoption area figures for earlier years are not available).

Table 1.8: Aggregate economic surplus for adoption of KM 94 in Vietnam.

Year	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Projected adoption profile - % area under KM 94	0.1	0.8	2.3	6.1	15.1	31.5	51.7	67.1	75.1	78.5	79.8
Projected area under KM 94 (million ha)	0.002	0.005	0.01	0.03	0.08	0.18	0.29	0.38	0.42	0.44	0.45
Aggregate economic surplus (million 1995 US $)	0.2	0.6	1.6	4.4	10.7	22.4	36.8	47.7	53.4	55.8	56.7
NPV of economic surplus flow from 1995-2010 (base year 1995 and discount rate of 5%) = US $149.91 million											

Aggregate economic surplus on account of adoption of KM 94 in Vietnam is estimated at US $47.7 million at the adoption area reached in 2008 and would increase to US $56.7 million at the adoption ceiling of 80%. Over the period 1995-2010, the net present value of the economic surplus generated by KM 94, assuming a discount rate of 5%, is US $ 149.91 million. The larger economic surplus generated in Vietnam in the later years (in spite of the much larger production and area under cassava in Thailand) is because of the low yield levels at the start of adoption in Vietnam and the higher proportion of area under adoption. Yield levels in Vietnam were only 50% of the yields in Thailand when KM 94 was introduced into Vietnam. The annual aggregate economic surplus associated with the use of KM 94 will decline as it is replaced by newer varieties and its area share declines. Again, it should be noted that these figures relate to the producer surplus attributable to the variety innovation alone.

Impact on Poverty
The estimates of aggregate economic surplus presented above reflect the gains in producer surplus as a result of adoption of KU 50/KM 94. Under the assumptions made, this figure provides a close approximation of the benefits accruing to producer households at different levels of adoption calculated as:

Total expected benefits = Benefits per hectare * Hectares of adoption

The aggregate economic surplus figures can be regarded as lower bound estimates of benefits to cassava farmers as they are based on fairly conservative assessments of the yield advantage provided

by KU 50/KM 94. We do not have poverty indices for the cassava growing regions of Thailand and Vietnam that could be used to weight the expected benefits to derive estimates of benefits accruing to the poor. However, cassava in Thailand and Vietnam is grown predominantly by farmers with holdings of less than 5 hectares, often in marginal environments. Therefore, it is suggested that estimated benefits to cassava farmers accrue predominantly to the poor.

Returns to research investment

KU 50 is a cassava variety that was developed and disseminated through a collaborative research effort between CIAT and the NARS in Thailand and Vietnam. An analysis of the returns to investment in the development of KU 50 requires the comparison of the economic benefits derived from the adoption of the variety with the development and dissemination costs incurred by both national and international partners. Collaborative research programmes (e.g., those between CGIAR institutions and NARS) may be intended to develop a stream of new varieties to meet the requirement of national partners. Such research programmes may cover more than one crop and may have other objectives (e.g. livelihood improvement) that go well beyond the development and dissemination of new varieties. It is, therefore, difficult to identify the research costs that could be attributed to the development of an individual variety. In assessing the returns from the development of a single variety, it may be appropriate to simply compare the magnitude of economic benefits by the adoption of a variety with the scale of the research programme that was responsible for its development.

CIAT attempted a detailed cost-benefit analysis of cassava varieties developed in S.E. Asia through collaborative research programmes (Ebata, 2011). The key features of this study, which covers China, Cambodia, Thailand and Vietnam over the period 1991-2009, were the following:

- Programmes of international and national organizations having a bearing on cassava research over this period were identified. Where programmes covered several crops or had multiple objectives, the proportion of expenditure attributable to cassava research was identified through a variety of data sources and expert opinion.
- Cassava research costs related to individual varieties were derived by allocating the total research costs on the basis of the adoption share of individual varieties in each country in each year[4].
- Benefits flowing from the adoption of individual varieties were estimated using standard economic surplus models (Alston et al., 1995).

The results of this study are summarized in Table 1.9.

Over the period 1991-2009, cassava research efforts by national and international institutions generated net benefits of US $ 9 billion in Thailand, of which KU 50 contributed US $ 3.9 billion. In Vietnam the net benefits were US $ 1.32 billion of which KM 94 contributed US $ 1.22 billion. The internal rate of return (IRR) for KM 94 in Vietnam was estimated at 345%[5]. KU 50/KM 94 made the largest contribution to net benefits from cassava research over this period. The total research cost attributable to KU 50 was only US $ 21.6 million, and US $ 2.39 million for Vietnam.

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[4] It is unlikely that the development costs of an individual variety would depend on its adoption area (although dissemination costs may be related to the extent of adoption). This method of allocation, however, has the advantage that a higher proportion of research costs would be attributed to the most successful varieties.

[5] The IRR for KU 50 could not be estimated as the benefits exceeded research costs in all years.

Table 1.9: Cost-benefit analysis of new cassava varieties in Thailand and Vietnam – US (1991) $ million.

Thailand						
Varieties	Rayong 3	Rayong 5	Rayong 60	Rayong 90	KU 50	Total
Consumer Surplus	77.50	234.76	152.00	228.65	686.03	1,378.95
Producer Surplus	970.58	2,256.43	1,949.91	2,549.87	6,898.26	14,625.04
Total Surplus	1,048.08	2,491.18	2,101.91	2,778.52	7,584.29	16,003.99
Cost of Research	5.13	7.62	7.96	9.43	21.60	51.75
Net Benefit	1,042.95	2,483.56	2,093.95	2,769.09	7,562.69	15,952.24
NPV	705.74	1,309.92	1,437.71	1,698.14	3,932.12	9,083.63
IRR	NA	NA	NA	NA	NA	
Vietnam						
Varieties	KM-94	KM-140	KM-98-5	KM-98-1	SM-937-26	Total
Consumer Surplus						
Producer Surplus	1,229.01	13.81	11.86	32.46	36.78	1,323.92
Total Surplus	1,229.01	13.81	11.86	32.46	36.78	1,323.92
Cost of Research	2.39	0.04	0.03	0.05	0.07	2.59
Net Benefit	1,226.62	13.77	11.82	32.40	36.70	1,321.32
NPV	583.35	5.68	4.87	14.53	17.72	626.14
IRR (%)	345.29	52.97	51.50	80.51	150.15	

(Source: Ebata, 2011)

Net present values (NPVs) and IRRs derived from the estimates of economic surplus in Table 1.7 and Table 1.8 would be lower that discounted values of net benefits in the CIAT study[6]. **However, setting the total research costs for KU 50/KM 94 of around US $ 25 million against the annual aggregate economic surplus of US $ 44.1 million for Thailand and US $ 53.4 million for Vietnam (at the respective adoption ceilings)[Tables 1.7 & 1.8] would still yield high rates of return for the investment in the development of KU 50/KM 94.** The rates of return would also be high in terms of the benefits accruing to cassava farmers (producer benefits) or benefits accruing to the poor.

The research costs included in the above analysis included only the costs of the national and international breeding programmes and did not include the costs of conservation and distribution of germplasm from the CIAT genebank, which facilitated the development of KU 50. When considering the benefits derived from the adoption of single new variety, it is conceptually difficult to identify the genebank costs related to its development. However, we can compare the magnitude of the costs of the CIAT genebank operations to the magnitude of benefits derived from individual new varieties developed using germplasm supplied by the genebank. Such comparisons can highlight the strong economic rationale for continued investment in conservation and distribution of germplasm through CG genebanks.

There have been several assessments of the costs of the CIAT genebank (Epperson, 1997; Koo, Pardey and Debouck, 2004; Horna et al., 2010), which conserves and distributes the germplasm of beans and tropical forages in addition to that of cassava. CIAT's own budgetary projections (CIAT, 2009) indicate that total outlay for the Genetic Resources Program (which covers genebank costs for all three crops) would be US$ 1.8 million in 2012. For cassava, where the CIAT genebank currently maintains over 6500 accessions, it has been estimated that the annualized costs for the maintenance and distribution of the cassava collection (including both capital and variable costs) would be of the order of US $

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[6] Although the methodology used for calculation of the economic surplus is similar to that used in the CIAT study, the results are different because of differences in (1) the initial year adopted for estimation in Thailand and Vietnam (2) the duration covered (3) profile of adoption area (which in our study is based on a fitted logistic curve) and (4) differences in the parameters used for calculation of economic surplus.

600,000 (Shands, 2011). The total costs of maintaining and distributing the collection *in perpetuity* have been estimated at US $ 3.36 million in 2008 (Horna et al., 2010). It would be difficult to estimate the costs of collecting the material that contributed to the economic impact of the improved cassava varieties as the missions took place long ago and did not necessarily involve CIAT. However, it is very unlikely that the costs were high, especially in comparison with the economic benefits generated through the breeding programmes.

It may, therefore, be seen that the total annualized (and in-perpetuity) genebank costs for the CIAT cassava collection are relatively small in relation to the magnitude of benefits derived from a single successful variety. The incorporation of genebank costs in the cost-benefit analysis of variety development will have an insignificant impact on the NPV of economic surplus estimates. It is, no doubt, true that not all varieties developed using materials from the CIAT genebank will be as commercially successful as KU 50/KM 94. The key insight from the analysis is that the economic surplus generated from a few successful varieties is sufficient to justify the investment in the CIAT genebank.

While the CIAT genebank costs are small in relation to breeding programme costs, the genebank nevertheless plays a crucial role in making the variety innovations possible. As discussed in the next section, in the absence of access to material from the CIAT genebank and collaborative breeding programmes it is unlikely that the national programmes in Thailand and Vietnam would have been able to develop varieties such as KU 50/KM 94 or close alternatives. However, even delayed development of alternative varieties would have large economic consequences. A five-year delay in the development of KU 50 in Thailand would reduce the net present value of the economic surplus estimated in Table 1.7 from US $243.63 million to US $ 190.89 million. Similarly, a five-year delay in the introduction of KM 94 in Vietnam would reduce the economic surplus estimated in Table 1.8 from US $ 149.91 million to US $117. 46 million. The loss in economic surplus as a result of delayed development of innovations would be much larger than the annualized costs of CIAT genebank operations.

Summary of CIAT contribution to KU 50

- Original collection work to build up the CIAT genebank stock.
- Contribution to initiating the CIAT-Thailand collaborative programme.
- Extensive information on cassava accessions maintained by the CIAT genebank.
- 30 years of evaluation and breeding in Colombia and Thailand.
- Planning (joint) of the crossing programme to produce Rayong 90.
- Provision of the female parent of Rayong 90.
- Production (joint) of the true seed of the hybrid between Rayong 1 and Rayong 90 that led to the selection of KU 50.

Counterfactuals and conclusions
Regarding counterfactuals, the key question to be addressed is, 'What would have happened to Thai (and Vietnamese) cassava production had not CIAT supplied the germplasm that led to the production of KU 50 (KM 94)?' In the absence of an improved variety (to replace Rayong 1) it is unlikely that there would have been an immediate disaster, cassava cultivation would not have ceased, but the data plotted in Figure 1.3 indicate that yields per unit area of land had plateaued and were possibly falling in both Thailand and Vietnam prior to introduction of KU 50 and KM 94 respectively. Although data are not available, soil erosion was also accelerating prior to the introduction of the improved varieties. It might be suggested that an alternative crop to cassava represents a realistic counterfactual, but given that industry in the region was geared towards cassava (and cassava starch) and that alternative starch-producing crops (albeit different starch types) would not necessarily be suited to

the environment, it seems unlikely that cassava would have been set to disappear in favour of an alternative crop. In any case, even were cassava to be replaced by potatoes or maize, for example, they would quickly become susceptible to biotic stresses and would almost certainly require the attention of plant breeders and access to genetic resources to counter their biotic and abiotic stress problems.

Rayong 1 had been the cassava variety of choice for a long time in Thailand and it was recognized that replacement varieties were needed that were superior in dry matter/starch yield. The joint programme between CIAT and Thailand allowed the use of CIAT genebank material and expertise to be used in combination with Thai germplasm (which ultimately derived from Latin America) and expertise. Not only was KU 50 produced, but also several other popular varieties, including Rayong 90, Rayong 5, Rayong 72, Rayong 9, Huay Bong 60 and Huay Bong 80, were also produced as a result of the joint programme. In fact, nearly all cassava varieties currently grown in Thailand derive from CIAT crosses. Without access to CIAT material and breeding expertise it is unlikely that such substantial progress could have been made, or at least not so rapidly[7]. Genebank and breeding staff expertise has been used in Colombia and Thailand for over 30 years. Thai cassava production was in a state of decline prior to the joint programme being established, although it is unlikely that production would have completely collapsed, at least not instantly, had there been no input of improved germplasm. CIAT expertise and germplasm also contributed to the decline in soil erosion/degradation in Thailand, although this component is even more difficult to assign a value than the germplasm.

Naturally, the cassava germplasm itself might be regarded as being of little or no value unless it is incorporated into a research or breeding programme, but its value actually lies in the entire collection representing a vast genepool from which selection can be done. Therefore, it is unrealistic to attribute value solely to specific accessions. However, growing the parents of KU 50 rather than the product of their crossing might furnish data that could indicate the division of attribution between germplasm and associated research/breeding. Unfortunately such data are not available, but the head of the cassava improvement programme at CIAT suggested an approximate division of 50:50 (C. Hershey, pers. comm.), which is more intuitive than accurate.

There were no institutions other than CIAT able to provide Asian programmes with a broad range of cassava genetic diversity and improved breeding populations based on crosses among genebank accessions. This was particularly true in the 1970s through to the 1990s, and is currently still the case. Quarantine regulations largely prohibit the introduction of germplasm from Africa or India into S.E. Asia because of the possibility of introducing cassava mosaic virus, which is not known outside of Africa and South Asia. The genetic diversity of cassava in Asia was very narrow prior to the large-scale introductions from CIAT. Through the 1980s most of Thailand (about 1 million hectares) was planted to a just Rayong 1. So within Thailand there was virtually no variability on which to draw for generating improved cassava varieties. Indonesia has moderate genetic variability (much of which is held in CIAT's genebank), but far less than is available at CIAT, and their breeding programme did not have the capacity or the motivation to develop improved materials to meet Thailand's (or other countries') particular needs. Thus there is a very clear link between the production and impact of KU 50 in Thailand (KM 94 in Vietnam) and the germplasm contained in the CIAT genebank and this link would have been difficult, if not impossible, to forge had not CIAT been able to provide parental material and associated expertise in selection and breeding. The actual parental material that contributed to the breeding of KU 50 (KM 94) is theoretically available, or at least present, in genebanks other than that of CIAT, but presence does not equate with availability or even reliability. Moreover, accessions are frequently misclassified and accession identifiers change according to genebank, country etc. such that definitive identification is often difficult or impossible unless

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[7] KU 50 was developed using germplasm from the Virgin Islands and Venezuela. In the absence of the CIAT genebank it may not have been possible for the national programmes to identify and access parental material necessary to achieve a breakthrough in the breeding programme. Although the International Treaty on Plant Genetic Resources for Food and Agriculture has put a Multilateral System (MLS) in place to facilitate the international exchange of germplasm of a range crops across countries, including cassava, the CG genebanks still play the dominant role in the transfers of germplasm to developing countries. Effective institutional mechanisms that would allow national programmes to source germplasm directly from centres of diversity/origin are yet to emerge.

synonyms are recorded accurately. In addition, genebanks are generally underfunded and often do not have the resources to conserve, evaluate, regenerate and distribute germplasm successfully. The CG genebanks, that of CIAT included, are able to fulfill these requirements and therefore often represent the only realistic source of the necessary germplasm for research and breeding programmes. That germplasm is also distributed by CG genebanks regardless of political considerations is also an important factor.

It could be asked whether it might be possible to re-collect the parental material accessions from their areas of origin. Unfortunately, this is unlikely to be possible. The collections were made before the advent of GPS, the collectors of the original material are unlikely to be traceable and a substantial amount of change has occurred in Venezuela that would probably mean that CM 76 no longer exists at the original site. Regarding V 43, little is known about it other than it originated from the Virgin Islands. Caribbean cassavas have been under enormous pressure and genetic erosion, including complete disappearance, has been a characteristic feature over recent decades.

Until the cooperative breeding programme with CIAT was established there had been virtually no progress in producing an improved cassava variety superior to Rayong 1, although it was recognized that one was needed. Had KU 50 not been bred, it is likely that another variety would have been bred by the Thai organizations, but progress relied on having access to a broad genetic base, which was (is) only to be found among the CIAT genebank materials. Other cooperative programmes might have been established between Brazil and Thailand, for example, which might have improved Thai cassava production, but only the CGIAR has a global mandate (IITA also has a cassava improvement programme, but it focuses on Africa and export of cassava material from Africa is problematic for phytosanitary reasons).

In terms of characterization and evaluation, CIAT is at an advantage as it can screen material in and generate useful data from a range of environments. Other cassava breeding programmes are unable to do this. KU 50, in fact, performs very poorly under Colombian conditions, but its potential was recognized through screening and characterization in S.E. Asia. Costing such characterization and evaluation would be difficult, and largely artificial, because not only are both activities long-term and based on multiple sites, but breeders simultaneously take into account a range of desirable traits for various facets of their breeding programmes.

The issue of time has to be considered in the case of developing KU 50. Rayong 1 had been the preferred of Thailand for a very long time. In the absence of a collaborative breeding programme with CIAT, it is difficult to imagine that the problems associated with a narrow genetic base could have been overcome quickly. Because the CIAT cassava collection was extensive and well evaluated, it was possible to select appropriate parental material for crossing without the need for further extensive evaluation. The Thai NARS were thus saved a considerable amount of time and expense, which translates into substantial economic benefits being realized much early than would have otherwise been the case, assuming that equally valuable breeding material could have been secured from elsewhere (which as argued is unlikely to have been the case).

The maintenance of cassava material in the CIAT genebank, *in vitro* and in the field, is relatively inexpensive given the returns to investment in cassava breeding. With over 6000 lines of cassava available in the CIAT genebank, CIAT represents the largest single source of genetic variation for cassava in the world. Therefore, simple identification of a suitable parents that led to the production of Rayong 90 was enough to break the trend in declining yields of Rayong 1, and eventually lead to a new cassava variety, KU 50 (KM 94), which became the world's most grown cassava. The CIAT cassava genebank will be used to an even greater extent in the future as a comprehensive new round of evaluation is undertaken to identify valuable traits that were not recognized during previous cycles of evaluation (Hernan Ceballos, pers. comm.).

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Appendix-1
Calculation of Economic Surplus from New Variety Adoption

Following Alston, Norton and Pardey (1995) and Fuglie (2007) the estimates of economic surplus derived from new variety adoption are derived from the following expressions:

(1) $\Delta TS = P_0 Q_0 (1-U_s) K (1+0.5 Z \eta_a)$

(2) $\Delta CS = P_0 Q_0 (1-U_s) Z (1+0.5 Z \eta_a)$

(3) $\Delta PS = \Delta TS - \Delta CS$

with $K = A_T \left(\dfrac{\Delta Y}{\varepsilon} + \dfrac{\Delta C}{P_0 Y_0} \right)$ and $Z = \dfrac{K \varepsilon}{\eta_a + \varepsilon} = (P_0 - P_1)/P_0$

Where:
ΔTS = Total economic surplus
ΔPS = Producer surplus
ΔCS = Consumer surplus
P_0 = Initial market price of the commodity (US \$ t^{-1})
P_1 = Market price of the commodity after adoption (US \$ t^{-1})
Q_0 = Initial market supply of the commodity (t)
U_s = Share of production retained for use as 'seed' (%)
A_T = Expected adoption ceiling (% of area)
Y = Initial average yield (t ha^{-1})
ΔY = Change in yield from adoption of new variety (% of initial yield)
ΔC = Change in production cost from new variety adoption (US \$ ha^{-1})
ε = Price elasticity of supply of the commodity
η_a = Price elasticity of demand (in absolute value) averaged across all uses of the commodity (as food, animal feed, marketed surplus etc.)

In the above equations, U_s is the share of production retained for use as 'seed', so $Q_0(1-U_s)$ is the net usable production. Z is the price effect measured as a percent change in initial price – and takes a positive value when the price falls. K is a measure of cost savings, as percent of the total value of initial production, resulting from new variety adoption resulting from higher yields and/or lower input use. A good approximation of the changes in total economic surplus[8] as a result of the adoption of the innovation is simply $P_0 Q_0 (1-U_s) K$, which is the measure we use to assess the aggregate economic benefits of adoption.

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[8] Fuglie (2007) notes that if $\varepsilon = 1$ and $\eta_a = 0$ then the total expected benefits from the above equation will be exactly equal to $P_0 Q_0 (1-U_s) K$. We have used this approximation mainly on account of data constraints. This approximation has been previously used in CIP research assessments (e.g., Walker and Collion: 1997).

Case-study 2 - Cooperation-88 (C88) potato

Summary

Cooperation-88 (C88) is a widely adapted, high yielding potato variety developed through a joint programme established between CIP (Centro Internacional de la Papa) and Chinese NARS to improve late blight resistance in potato adapted to the sub-tropical highlands. Late blight is globally the most serious threat to potato production, accounting for €1 billion each year in lost production and control. C88 is currently grown on about 400,000 hectares in five provinces of southwestern China, the largest area being planted in Yunnan. C88 is replacing Mira - a variety of German origin that at its peak was grown on nearly a million hectares in China - as it becomes increasingly susceptible to late blight and viruses. C88 was bred by crossing several *Solanum* species including *andigena, tuberosum and demissum.* The germplasm for the maternal parent was evaluated by CIP breeders and the Yunnan Normal University. The male parent was derived from a complex pollen bulk of potato crosses made for an MSc. project in the Philippines. True potato seed was evaluated in China and after 5 years of trials and selection, clone #88 was identified as a high-yielding, late blight resistant clone, which was adapted to longer day growing conditions. The variety was named Cooperation-88 and launched as a variety in 1996. It is estimated that the economic benefits accruing from C88 adoption in China at the level of adoption in 2010 were US $ 350 million and will increase to US $ 465 million per year if an adoption ceiling of 600,000 hectares is reached in 6-8 years. C88 has also stimulated growth in the potato processing industry, as it is suitable for both the table and chipping. The adoption of C88 is having a substantial impact on poverty, providing economic benefits to the poor estimated at $ US 192 million a year in 2010, a figure that is set to increase as adoption increases. Such an effective poverty alleviation instrument would not have been possible without the use of germplasm (particularly from native potato) conserved at the CIP genebank. This collection promises to be the source of further impacts as its true value becomes recognized through continued evaluation and research. Although China has its own national breeding programme, it is seeking to improve disease resistance in its commercial varieties. Inclusion of CIP genebank material in C88 has broadened the genetic base of potato in China and diminished production risks associated with late blight susceptibility. C88 is currently one of the most widely grown potato varieties in the world and its area is set to increase further.

Potato and late blight

Potato plays a vital role in global food security, feeding more than a billion people with an annual production of over 300 million tonnes in more than one hundred countries. Half of global potato production comes from developing countries.

Cultivated potato occurs as two subspecies of *Solanum tuberosum*, *tuberosum* and *andigena*, and there are nearly two hundred wild potato relatives, mainly from the centre of origin, the Peruvian-Bolivian Andes. One wild relative, *S. demissum*, has been used extensively since the 1950s in potato breeding as a source of genes for resistance to major fungal and viral diseases (Black et al., 1953). A principal disease of potato in most places where it is grown is late blight (LB), *Phytophthora infestans*. This was the cause of the European (Irish) potato famine in the 1840s. This disease continues to represent the greatest challenge to potato production and is a major concern of all potato breeders. Its control through host-plant resistance represents a central plank of the International Potato Center's (CIP) strategy to supply improved potato germplasm worldwide. Although fungicides can largely be used to manage LB, agrochemical control is not necessarily an economically viable or realistic option for many smallholder potato growers and resistance breeding therefore often represents the only chance to secure the yield (realizing that breeding cannot completely substitute for fungicide control of LB). Jansky et al. (2009) state that disease pressure is often severe in potato fields in China largely because the use of fungicides is limited or non-existent in most production areas. The direct annual monetary costs of control of LB and lost production are estimated at €1 billion worldwide (Haverkort et al., 2008). In the absence of resistant potato varieties, these costs are likely to increase as potato production areas rapidly increase in developing countries, particularly in China, India and the highlands of several African countries (Fry, 2008; Vleeshouwers et al., 2011).

Potato production in China

Potato production has experienced marked growth in China during the last twenty years and China became the world's largest producer of potatoes in 1993. It remains the world's top producer, with 73 million tonnes of potato produced in 2010 (FAOSTAT).

Between 1985 and 2010, the area devoted to potato in China expanded from 2.48 million hectares to 5.08 million hectares and production trebled from 26.79 million tonnes to 74.79 million tonnes (Figure 2.1). In 2010 China accounted for 27% of the global potato area and 23% of the total production (FAOSTAT). Per unit area yield increased during this period from 10.8 t ha^{-1} to 14.73 t ha^{-1} (Figure 2.2), narrowing the yield gap with respect to mean global yields, which were about 63% in the mid-1980s and now exceed 85% of global yields. The increase in popularity of potato has been driven by growing demand; between 1978 and 2001 the area devoted to potatoes increased by 87.4% for (Wang and Zhang, 2004). In 1961-1990 per capita potato consumption in China was about 12 kg, but by 2007 had reached 31.5 kg (FAOSTAT).

Figure 2.1: Growth of potato area and production in China (1985-2010).
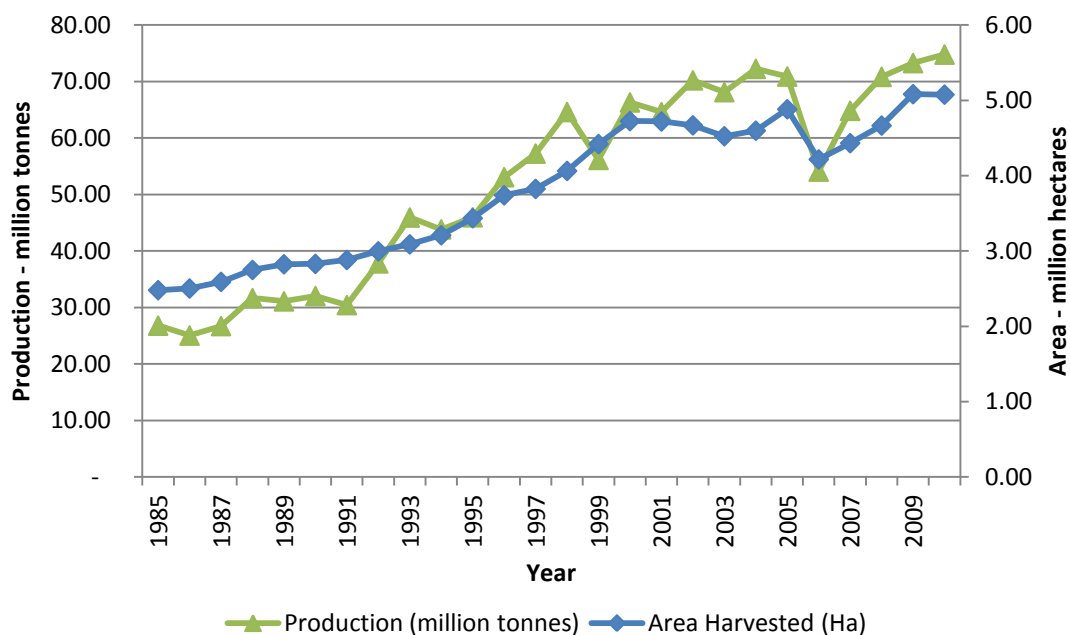
(Source: FAOSTAT)

Figure 2.2: Growth in potato yields in China (1985-2010).
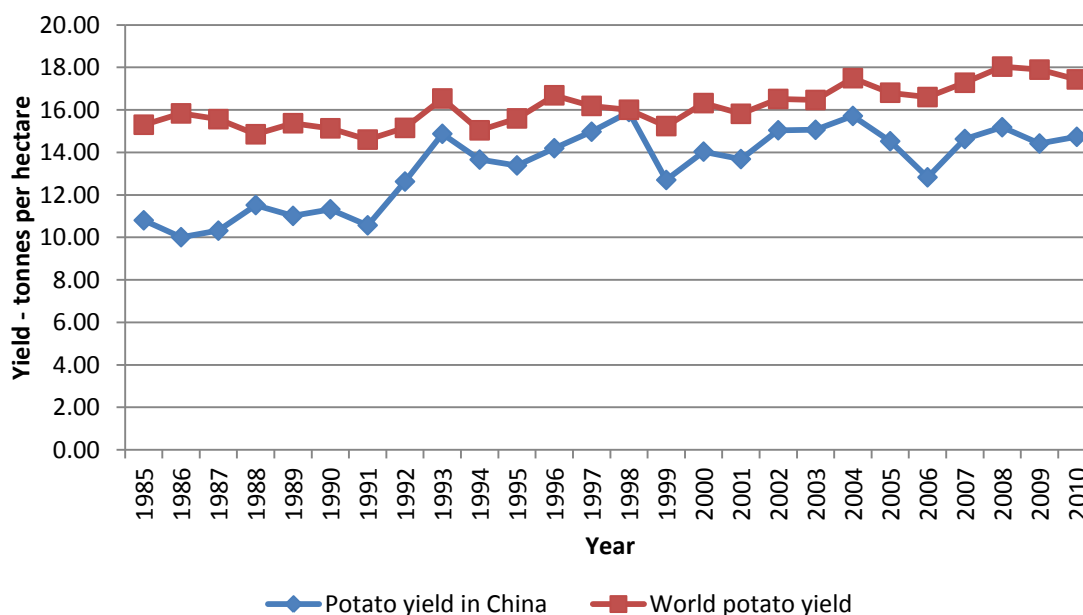
(Source: FAOSTAT)

While there is clear evidence of a dramatic increase in potato production in China since the mid-1990s, it should be noted that potato statistics in China are subject to considerable uncertainty and have undergone several revisions (Scott and Suarez, 2012). FAOSTAT time series on Chinese production and area since 1961 have been revised twice and there are still large differences in the area and yield estimates between FAOSTAT and Chinese national agricultural statistics –with FAOSTAT estimates being more conservative for area and yield. These differences in basic potato statistics from different sources make it difficult to estimate reliable trend rates of growth in area, production and yields. Scott and Suarez (2012) note that factors affecting the reliability of national statistics include:

(a) The practice of expressing potato production in "grain equivalent" terms with equivalence ratios varying across provinces and over time.

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(b) The recent (post-2006) "reclassification" of potato as a vegetable in some provinces (e.g., Guangxi) rather than as a staple, leading to exclusion/reduction of potato areas from agricultural statistics in some provinces.

(c) The lack of data to disaggregate total area and production of root and tuber crops by individual crops.

The increase in importance of potato in China has resulted in a rapidly expanding processing industry (Ma, Shuping, 2010):

- About 5000 enterprises (140 large-scale)
- Two million tonnes of refined starch production capacity with an output of 300,000 tonnes
- 10 companies with a total production capacity of 100,000 tonnes of potato flour and output 30,000 tonnes
- About 30 companies producing chips at a capacity of 130,000 tonnes
- Potato starch noodle processing capacity of 80,000 tonnes

There are four major zones in China where potatoes are grown:

- The northern single-cropping zone
- The south-western mixed cropping zone
- The central double cropping zone
- The winter cropping zone

The south-western mixed cropping zone accounts for about 40% of potato production in China (Jansky et al., 2009). Potatoes can be grown year round in this zone, but above 2000 m, in the highlands, they are principally a summer crop, grown from April to September. In other regions potatoes are grown as an autumn crop (July to December), a winter crop (October to March) or an early spring crop (December to May).

The CIP-China cooperative breeding programme
Jansky et al. (2009) stated that potato breeding in China did not really begin until the 1940s with the introduction of imported varieties that were intercrossed and selfed to generate segregating populations for selection. This has resulted in the narrow genetic base and extensive common parentage of Chinese potato varieties. The programme of cooperation between CIP and Yunnan Normal University (YNU) was initiated in 1986. The focus was on selecting high-yielding clones for the south-western (sub-tropical highland) Chinese environment that had superior resistance to LB and the common viral diseases.

A second objective was to develop seed tuber production based on tissue culture and virus clean-up of superior potato germplasm. Germplasm from the CIP genebank was supplied for evaluation as parental material under Chinese conditions in 1986. Several clones were provided by the genebank and four were identified as potential female parents: I-1085 (Sita – released in Sri Lanka in 1981), CIP-24 (Achirana Inta), CIP 378711.7 and CFK69.1. All four clones were known (from previous screening) for their relatively high levels of resistance to LB and yield potential that exceeded that of the check variety Mira, a popular NARS-produced potato variety that originated from Germany.

The evaluation and breeding scheme
The joint breeding programme began in 1986 when a CIP-supported Vietnamese graduate student, Dao Hui Chien, as a part of his MSc. Studies at Benguet State University (Philippines), identified LB resistant CIP clones adapted to sub-tropical highland conditions in the Philippines during an extensive screening-evaluation exercise. This work was done in cooperation with Professor Wang Jun (formerly

of YNU) and Professor Canhui Li (YNU). Peter Schmiediche, a CIP scientist, was responsible for breeding the advanced clones, screened by Chien, from populations of native (*andigena*) and cultivated potatoes with high resistance to LB. These clones derived from the extensive collection of potato germplasm maintained by the CIP genebank.

The original work focused on screening 505 CIP potato clones, comprising both *tuberosum* and *andigena* germplasm, for resistance to LB. Following extensive evaluation over two years little progress was made. However, from the original collection of 505 clones, 15 were selected for further research and crossing (Chien, 1989). These are listed in Table 2.1.

Table 2.1: Initial selection of clones from evaluation in Benguet from June 20th to September 8th 1986 (Chien 1989).

LBR clone	CIP identifier	Pedigree
0-6	381400.22	787 x Bulk Mex
0-1	380014.11	Greta x CCV69.1
0-2	380479.6	I-967 x Bulk LT-7
0-12	382181.3	378508.227 x Bulk LB
0-11	382152.2	377936.6 x Bulk Mex
0-9	382152.2	377936.6 x Bulk Mex
0-5	381397.6	721 x Bulk Mex
0-10	382152.3	377936.6 x Bulk Mex
0-13	382251.19	377852.1 x I-1035
0-14	383017.1	380493.18 x R128.6
0-7	382119.6	277 x Bulk Mex
0-15	383074.2	80-H-4 x R128.6
0-3	381376.1	Monserrate x I-1158 x Bulk early
0-4	381397.2	721 x Bulk Mex
0-8	382132.14	378971.152 x Bulk Mex

The identifiers in Table 2.1 appear also in Figure 2.4. The 15 clones represent the first cycle of recurrent selection. Crossing was done in the field at the Northern Philippines Root Crop Research and Training Center between January 15th and May 15th 1987. Once the 15 clones (Table 2.1) were identified breeding followed a four-step scheme:

a. Bulked pollen of the 15 clones (BK LBR 0 Phil) was used in crosses with 8 CIP clones, a subset of the original 15 selected clones.

b. Seedlings of this cross were tested for LB resistance by artificially inoculating with *P. infestans* suspensions under greenhouse conditions. Only highly resistant seedlings were transplanted into the field for further LB evaluation.

c. Outstanding LB resistant progenies from the first cycle of selection showed better adaptation to long days and were selected as male parents (pollen bulk called BK LBR 1 Phil) and crossed with the 8 clones.

d. Seedlings were subject to a second cycle of recurrent selection under greenhouse and field conditions. The pollen bulk of the best lines (BK LBR 2 Phil) was used to cross with I-1085.

Between 1987 and 1989 a large evaluation programme was undertaken in the greenhouse and field to identify LB resistant germplasm. This evaluation effort should not be underestimated as it was key to producing C88. Much of the original germplasm derived directly from the CIP genebank. Suffice it to say, without CIP germplasm and CIP breeding expertise the work described here would not have been possible.

The female parent was selected in China from among the better-adapted clones and through a complex series of crosses the LB-resistant clones were used as a source of bulk pollen (male parent). Despite the clones being LB resistant they were not adapted to long-day conditions. Over 8,000 true (botanical) seeds were produced in 1990 from a cross between the female parent I-1085 and a bulk of pollen sources as the male parent. Nine rounds of selection for agronomic characters, and particularly for LB resistance, were undertaken in China at the Agricultural Extension Station in Huize over five years. This led to identification of #88, which was released in Yunnan Province in 1996 as Cooperation-88, abbreviated to C88 (He and Wang, 1993). The name was intentionally chosen to reflect the co-operation between CIP and the Chinese scientists. YNU carried out meristem culture to rid the material of viruses and clean mini-tubers were produced in 1995.

C88 has been tested annually under typical growing conditions, where it has been shown to possess resistance to all prevalent LB pathotypes. C88 possesses high levels of resistance to two major viruses, PVY° and PVX, and moderate resistance to PLRV. C88 also has various levels of resistance to a range of other pests and pathogens (Li et al., 2007).

C88 became valued as both a table variety (large tubers), where it attracts a price premium over Mira, and is also suited to the potato chip industry (medium-sized tubers). Small tubers are kept for seed (Li et al., 2007). C88 can be grown during summer and winter cycles as it is day-length insensitive.

Other sibling clones of C88 (particularly LBR 1-5) identified by Chien in his thesis work have become preferred varieties in the Philippine highlands (Igorota) and in the southern highlands of Vietnam (PO-3), where in each country about 70% of the potato-growing area is devoted to them[9]. Thus, the development and success of C88, while representing the major impact of the collaborative work, was not the sole impact.

Origins of the germplasm
<u>*The female parent*</u>
The female parent of C88 was I-1085 (Sita), a high-yielding commercial potato from the Indian national potato breeding programme, which had been screened for LB resistance in Mexico and was obtained by CIP for distribution and research. I-1085 was released as a variety in 1991 in China by YNU after its receipt in 1986, but with limited success. Although CIP evaluated I-1085, it did not otherwise play a role in its development. However, identification of I-1085 as a suitable female parent came after rigorous selection among a range of varieties and advanced clones for LB resistance, which drew heavily on the genebank accessions. Three other clones/varieties, which did have CIP backgrounds, were included in the final evaluation: CIP-24 (Achirana Inta), CIP 378711.7 and CFK 69.1.

It is important to know something about the genetic background of the female parent of C88 as it contains a number of potential sources of LB resistance incorporated from *S. demissum*, a wild species of potato. The parentage of I-1085 can accurately be traced back to the German potato breeding of the early 1900s, and comprised several varieties and breeders' lines (see Figure 2.1). Hetman, for example, entered the German national List in 1902, Capella was on the list in 1943 and Schwalbe in 1956.

Capella probably derived some of its LB resistance from the inclusion of *S. demissum* genes that were contributed through Edda. More LB resistance genes probably entered via Aga, whose parents were Panther and the same line (4242) used as a male parent to Edda, though used as a female to produce Aga. Native potato genes and *S. demissum* genes also entered I-1085 via Hindenburg. The durable resistance of C88 to LB, which has been attributed to its native potato background (also from Lopez and the pollen bulk on the male side), gives it a great advantage over Mira.

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[9] Pers. comm. Peter Vanderzaag, who is currently working on a publication concerning Igorota and PO-3.

The basic pedigree of I-1085 can be traced through the European Cultivated Potato Database (http://www.europotato.org/varietyindex.php).

Figure 2.3: The pedigree of I-1085, the female parent of C88.
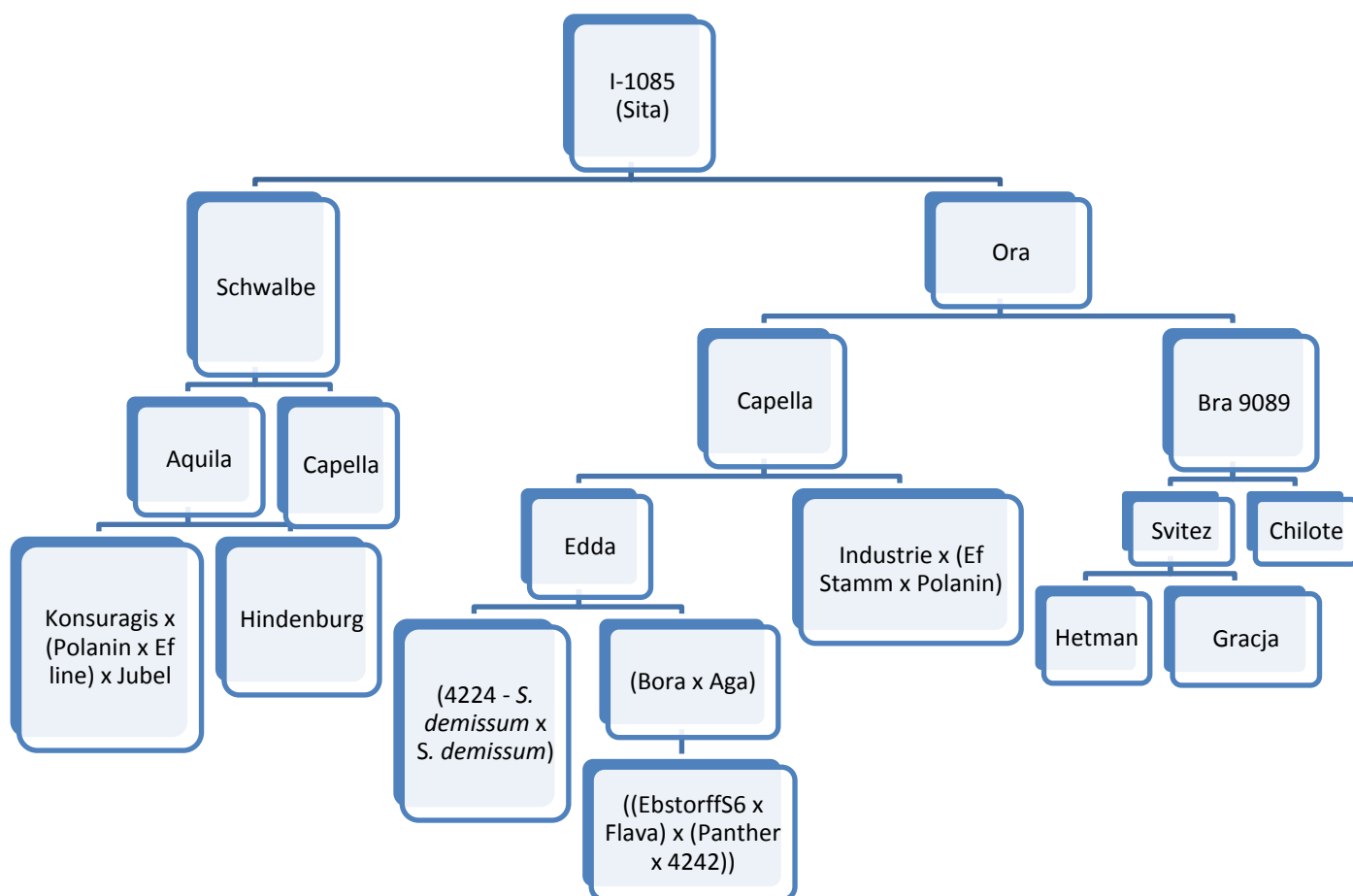

The male parent

It is through development of the male parent to C88 that CIP made a major contribution. Development of the male parent relied heavily on extensive characterization and evaluation of numerous native potato accessions from among the unique collection conserved in the CIP genebank (4732 accessions as of 2012). This collection was built up over many years and includes material from numerous sites in Latin America. The male parent was a bulk pollen source from a large population of LB resistant clones selected by Chien during two cycles of recurrent selection in the northern highlands of the Philippines in 1986.

The pedigree of one of 15 clones used as a pollen donor to the bulk population (BK2) is given in Figure 2.4 (it is not useful to include a further 14 diagrams). The germplasm that contributed to the male parent of C88 can be traced back to CIP's potato genebank using the accession numbers provided (www.cipotato.org/genebank), but the process is not as straightforward as for the female parent pedigree.

Figure 2.4: The pedigree of one (381400.22) of the 15 original clones that comprised the bulk pollen of the male parent of C88.
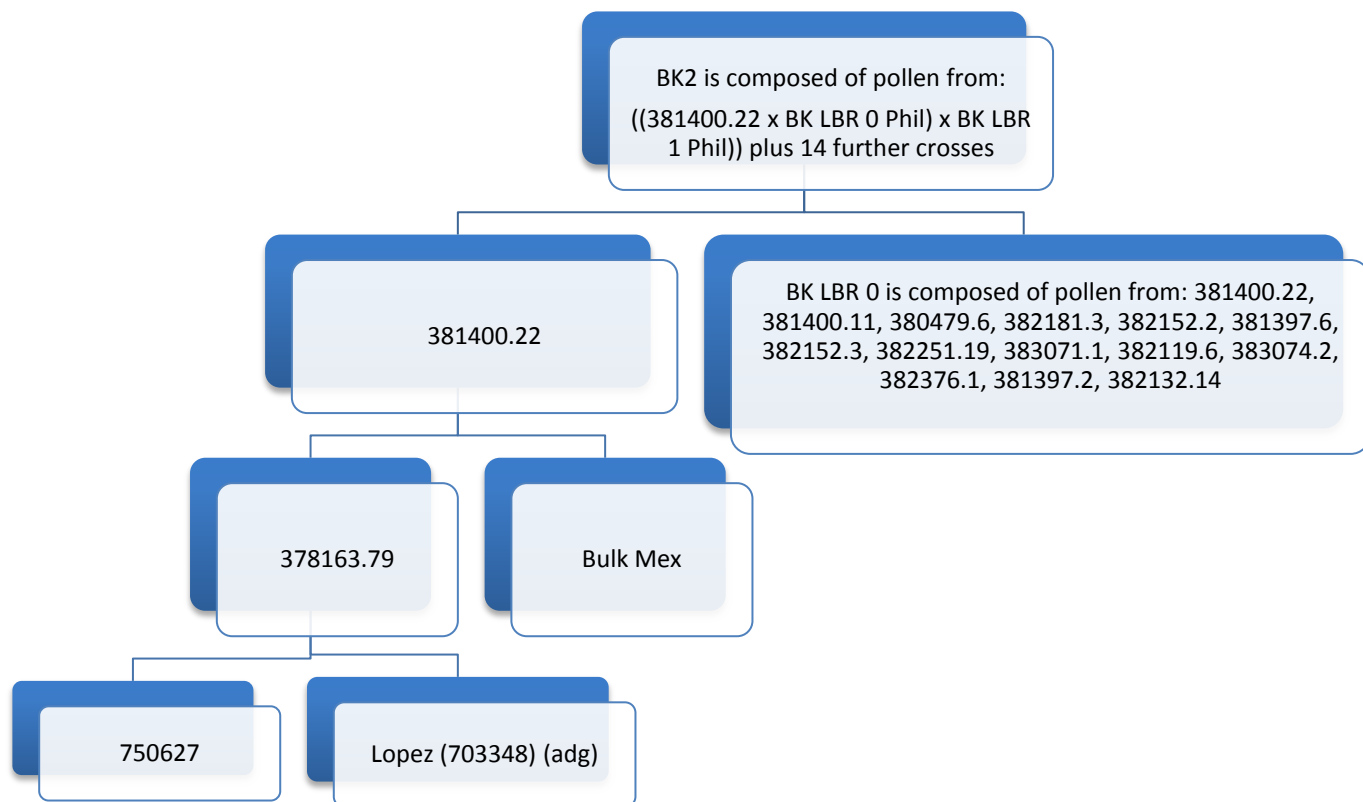
Adoption

Following release in 1996 in Yunnan province, C88 was rapidly adopted in neighbouring provinces over the following 15 years. It is estimated that the area under C88 is currently about 400,000 ha, which is nearly 20% of the potato area in the south-western production zone. This production area makes C88 one of the leading potato varieties in the world. In comparison, the leading cultivar in the USA and Canada, Russet Burbank, occupies an area of only 175,000 ha. Few potato cultivars cover a larger area than C88 (Li et al., 2011). In China the NARS cultivar Kexin 1 (the world's most planted potato variety) occupied over 900,000 ha in 2007, but could be declining in importance, similarly to Mira, which was ranked first in China in 1997, at nearly 950,000 ha, but fell to second place, at a little over 200,000 ha in 2007 (Thiele et al., 2008). During the same period C88 rose from 53rd to 9th in the country (Thiele et al., 2008). The progress of adoption of C88 in Yunnan province is summarized in Table 2.2.

Table 2.2: Adoption of C88 in Yunnan Province.

Year	Total potato area (ha)	Area planted to C88 (ha)	C88 area share of (%)	Variety rank
1997	249,300	2,666	1.07	6
2000	316,900	40,000	12.62	3
2002	348,000	76,867	22.09	3
2004	448,000	98,400	21.96	2
2006	539,000	133,333	24.69	2
2008	618,000	156,333	25.30	2
2009	634,100	186,667	29.44	1

(Source: Li et al., 2011)

The data in Table 2.2 highlight the speed of adoption of C88 in Yunnan province, where starting from a low base in 1997, it became the leading variety, occupying nearly 30% of the potato area within 12

years. The availability of a variety with resistance to LB also appears to have contributed to the marked expansion of potato area, by 154%, over this period. C88 has also spread to the neighbouring provinces of Guangxi, Guizhou, Sichuan and Chongqing and is reported to have spread into Vietnam and Myanmar through seed sales (Li et al., 2011). Although time-series data for adoption of C88 in the Chinese provinces are not available, the current area and area share of C88 is described in Table 2.3.

Table 2.3: Adoption of C88 in neighbouring provinces of Yunnan in 2009.

| Province	Area under C88 (ha)	Share of C88 in potato area
Guangxi	30,000	23%
Guizhou	96,670	15%
Sichuan	60,000	22%
Chongqing	16,670	5%

(Source: Area under C88 from Li et al. (2011) and share computed using provincial Chinese potato statistics compiled by Kaiyun Xie, CIP)

Thus, C88 has acquired a significant market share not only in Yunnan, but also in the neighbouring provinces of south-western China. An area share for a single potato variety in excess of 10% is remarkable considering that there are nearly 120 commercial varieties grown in China. If all provinces in the southwest production zone were to reach an area share of 30%, then the area under C88 would exceed 600,000 ha, making it one of the most successful potato varieties of all time. It is also possible that C88 could completely replace Mira as it becomes increasingly susceptible to LB and other serious diseases, and as LB fungicide-control costs rise.

We do not have estimates of area under C88 in Yunnan and neighbouring provinces on an annual basis after its introduction in 1996. To build up an adoption profile of C88 we have fitted a logistic curve to the available point estimates of area under C88 in different years. CIP (Thiele et al., 2008) estimated that area under C88 was 3,333 ha in 1997 and grew to 118, 000 ha by 2007[10]. Li et al. (2011) reported total area under C88 to be 390,000 ha in 2009. The adoption ceiling for fitting the logistic curve was taken as 600,000 ha, which would represent an area of 30% in the south west production zone. This may be regarded as a conservative ceiling as an area share of 30% has already been reached in Yunnan province. The estimated adoption area of C88 in China is presented in Figure 2.5. The adoption ceiling is expected to be reached by 2020.

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[10] It was acknowledged that the figure for 2007 was lower than that reported from a number of other sources. This figure is lower than the figure for Yunnan province alone estimated by Li et al. (2011).

Figure 2.5: Estimated adoption profile of C88 in China (1996-2020).
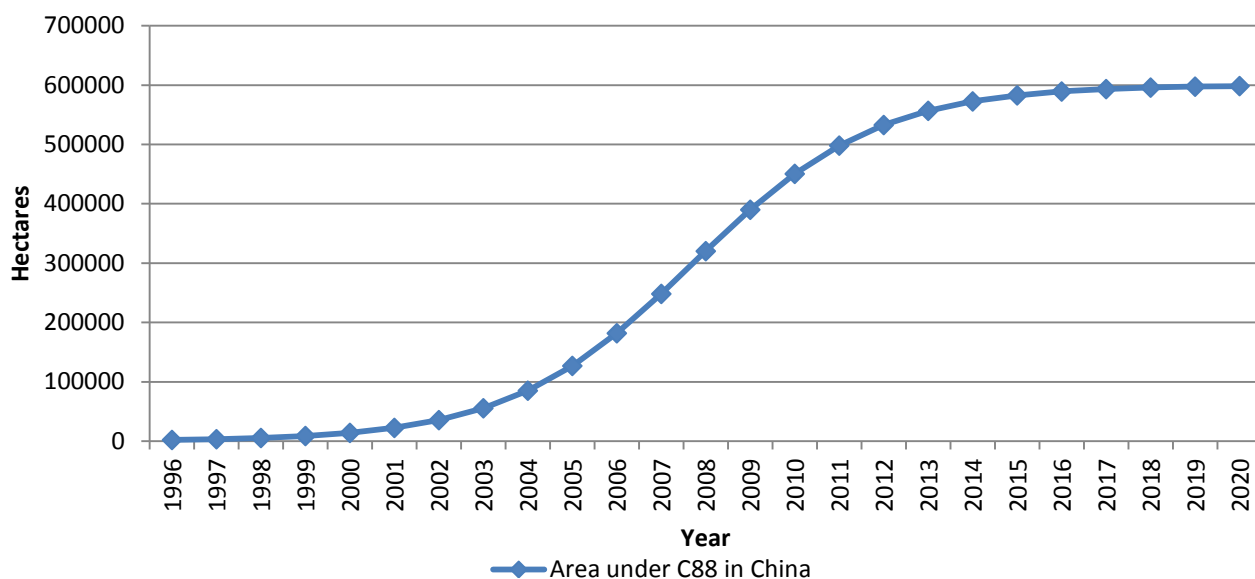
Yield advantage of C88

The rapid adoption of C88 in China followed the increasing susceptibility to LB in Mira, which was planted on 945,000 ha in 1997. C88 is now planted in areas previously planted to Mira, whose area declined to under 207,000 ha by 2007 (Thiele et al., 2008). In agronomic trials in 1994-95, C88 produced yields exceeding 50 t ha^{-1}, and the yield advantage in relation to Mira was nearly 36%. In subsequent trials, where farm-saved tubers were used, the yield declined to about 30 t ha^{-1}, but the yield advantage over Mira was still in the order of 40%. The yields of C88 under farm conditions in Yunnan and neighbouring provinces are summarized in Table 2.4.

Table 2.4: Yields of C88 in Chinese provinces in the south-western zone.

Province	Yield (t ha^{-1})
Yunnan	30.0
Guangxi	33.5
Guizhou	32.0
Sichuan	33.7
Chongqing	22.5

(Source: Li et al., 2011)

Estimation of economic surplus from C88 adoption

The standard approach to the assessment of economic surplus impacts following the adoption of innovations involve the following steps:

(a) Calculating a supply shift (K-shift), representing the unit cost reduction associated with the use of a new technology.
(b) Gathering information on expected adoption rates and their evolution over time.
(c) Combining the above information with market information on supply and demand elasticities and equilibrium prices and quantities (Alston et al., 1995).

The application of the standard approach to estimation of economic surplus by the adoption of C88 is not feasible as reliable data on several key parameters are not available, including the autonomous growth of supply and demand, supply and demand elasticities and producer prices in different provinces in different years. We have, therefore, used the "benefits from adoption" in each year as an estimate of the economic benefits generated by C88. The benefits of adoption in each year are estimated as:

Benefits per hectare x Area under adoption

Appendix-1 explains the assumptions under which the benefits from adoption, which reflects the benefits accruing to producers adopting the variety, provide a reasonable approximation of the economic benefits generated by a new variety[11]. We estimate the economic benefits generated over the period 1996 to 2020, when the adoption ceiling is expected to be reached (Figure 2.5).

The area under adoption in each year is based on the adoption profile of C88 estimated in the previous section. In 1996, prior to the introduction of C88, the average yield in the southwest production zone provinces was around 14 t ha^{-1}. In its Research Priority Assessment Exercise (2005-2010) CIP estimated (Fuglie, 2007) the benefits from the adoption of LB resistance technologies (through breeding and management) to be US $777 per hectare in LB affected areas, more than 50% of which were in China. The average benefits per hectare were derived from an expert panel assessment of the yield gains on account LB management (Anderson, 2008) of nearly 6 t ha^{-1} over an average yield of 14.5 t ha^{-1} (see Figure 2.6). The estimation of expected benefits per hectare also took into account reduction in fungicide costs of US $ 125 ha^{-1} and increases in costs associated with higher yield (e.g., harvesting costs).

Figure 2.6: Potato yield gap analysis in China.
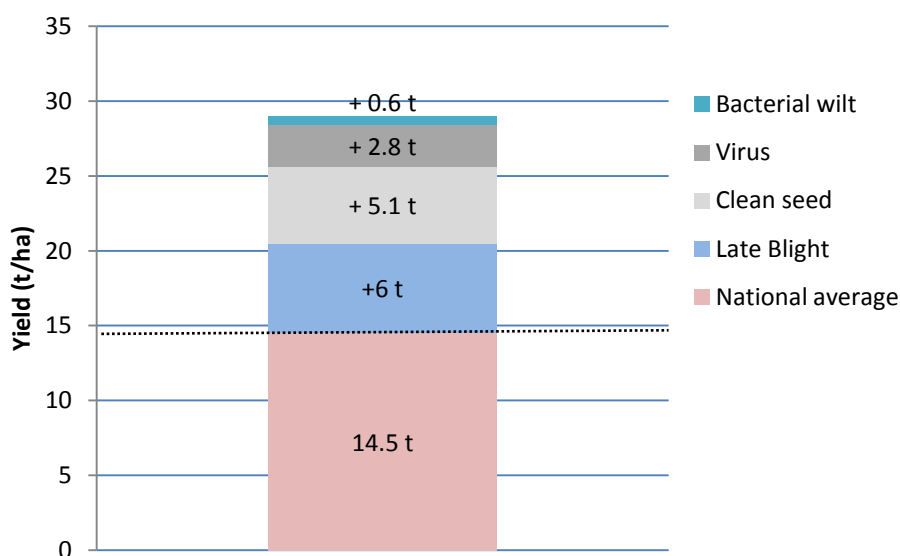
(Source: Anderson, 2008 and Fuglie, 2007)

Table 2.5 presents the estimates of the flow of economic benefits attributable to the adoption of C88 in China. The economic benefits from the adoption of C88 are estimated at US $ 350 million per year in 2010 and will increase to US $ 465 million per year when the adoption ceiling of 600,000 hectares is reached. The figures do not incorporate downstream surpluses, those generated by the processing

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[11] The total benefits of adoption computed in this way does not reflect the impact of price changes due to changes in supply resulting from the adoption of the innovation.

industry, for example, but only producer surpluses[12]. The downstream surpluses are likely to be substantial. The net present value of the benefit stream over the period 1996-2020, assuming a discount rate of 5%, would be US $2648 million.

Table 2.5: Economic benefits from the adoption of C88 in China (1996-2020).

Year	Estimated area under adoption (hectares)	Expected annual benefits of adoption at US $ 777 per hectare (US $ million)
1996	2,059	1.60
1997	3,333	2.59
1998	5,389	4.19
1999	8,694	6.76
2000	13,978	10.86
2001	22,354	17.37
2002	35,443	27.54
2003	55,463	43.09
2004	85,085	66.11
2005	126,844	98.56
2006	181,858	141.30
2007	248,216	192.86
2008	320,244	248.83
2009	390,000	303.03
2010	450,484	350.03
2011	498,099	387.02
2012	532,812	413.99
2013	556,727	432.58
2014	572,568	444.89
2015	582,789	452.83
2016	589,274	457.87
2017	593,343	461.03
2018	595,879	463.00
2019	597,453	464.22
2020	598,428	464.98
Net present value of the benefit stream over the period 1996-2020, assuming a discount rate of 5%, = US $ 2648 million.		

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[12] It should be noted that adopters of the new variety do not necessarily receive all of these benefits because this figure does not include the effect of downward pressure on market prices, which may pass on some of the benefits to consumers. Also non-adopters may share benefits of technologies that increase market demand, as this affects the prices received for the crop. However, the expected benefits of adoption do provide a robust approximation of the economic impacts of new variety adoption.

Impact on Poverty

The economic benefits generated by the adoption of C88 will not accrue entirely to the poor. The poverty impact of C88 adoption depends on the distribution of the economic benefits across households, which in turn depend on their socio-economic characteristics, their propensity to adopt the new technology and their status as net buyers or sellers of the commodity. When household level data are not available, the alternative approach suggested by Fuglie (2007) involves estimation of the total annual benefits of adoption and assessment of the share of benefits accruing to the poor based on poverty indices. Using this approach, an assessment made by CIP (Fuglie, 2007) estimated that the adoption of LB management technologies on a total global (affected) area of 693,000 ha would provide an annual aggregate economic surplus of US $ 319.4 million per year, of which nearly US $ 175.4 million (55% share) was likely to benefit poor households. If we assume that a similar share of the economic benefits from C88 adoption accrues to poor households in China, then at rates of adoption in 2010, C88 was already providing economic benefits to the poor in China estimated at US $192 million per year, which may increase to US $256 million per year when the anticipated adoption "ceiling" is reached. Thus, the benefits accruing to the poor in China *alone* through the adoption of C88 are set to exceed CIP estimates of benefits likely to accrue to the poor globally as a result of adoption of LB management technologies.

Returns to research investment

C88 was developed through a collaborative effort between CIP and the NARS in China. Therefore, a cost-benefit analysis of the returns to investment in the development of C88 needs to evaluate the economic benefits from C88 adoption with the costs incurred in the development and dissemination of the variety by CIP as well as the NARS in China. However, the research costs related to the development of LB management technologies have been assessed as part of the research priority setting exercise for 2005-2010 (Fuglie, 2007). Of CIP's total budget of around US $20 million, US $1.8 – US $2.0 million is the research expenditure devoted to LB management technologies. Data relating to research expenditures by NARS in China are not available[13]. Therefore, for the research priority setting exercise, the returns to investment in LB management technologies were assessed based on the following assumptions/scenarios:

(1) A planning horizon of 30 years and a discount rate of 3%, with research costs assumed to occur in the first 5 years of the planning horizon, extension lasting 10 years from year 6, adoption starting in year 6 and reaching an adoption ceiling after 10 or 20 years depending on the scenario assumed, and benefits continuing at this level till the end of the planning horizon.
(2) Adoption of ceiling of LB management technologies of 693,000 hectares ("status-quo adoption") or 1,577,000 hectares (high/enhanced adoption).
(3) Slow adoption (ceiling adoption reached by 2020) and fast adoption scenario (ceiling adoption reached by 2030).
(4) NARS research expenditure equivalent to CIP expenditure.
(5) Dissemination costs of US $16 per hectare. Dissemination/extension efforts assumed to be spread equally over 10 years and equal to ceiling adoption area multiplied by the dissemination costs per hectare.

Based on the above assumptions the Net Present Value and Internal Rates of Return assessed for aggregate economic benefits and benefits accruing to the poor are summarized in Table 2.6.

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[13] CIP is attempting to obtain the data from China.

Table 2.6: Cost Benefit Analysis of CIP potato research.

Technology	Adoption ceiling	Aggregate economic benefits (US $ million)				Benefits accruing to the poor (US $ million)			
		Rapid adoption (2020)		Slow adoption (2030)		Rapid adoption (2020)		Slow adoption (2030)	
		NPV	IRR	NPV	IRR	NPV	IRR	NPV	IRR
LB management	693,000	2820.4	57%	1787.7	39%	361.5	24%	209.6	16%
	1, 576,638	6039.8	57%	2143.4	40%	863.9	26%	505.4	17%

(Source: Fuglie, 2007)

The adoption of C88 over 400,000 hectares is probably already providing a large part of the anticipated benefits from the global (developing country) adoption of LB management technologies foreseen in CIP's research priority setting exercise. If a cost-benefit analysis were undertaken at the variety level by segregating research and dissemination costs, then the Net Present Value and Internal Rate of Return would be larger than reported for LB management technologies as a whole. **This would imply that C88 could probably be described as one of the most effective poverty alleviation instruments contributed by international agricultural research collaborations.**

Issues of restricted impact
Chinese legislation at central and provincial levels and institutional policy restricted the availability of C88 such that only Chinese growers had access to it, although Li et al. (2011) reported that C88 was being sold as seed tubers in Vietnam and Cambodia. The case seems to be one of 'a partial international good with some lost benefits', as poor farmers in other sub-tropical highland environments, such as the East African highlands and those in Bangladesh, have not been able to secure this potato variety and benefit from its enhanced LB resistance. The restricted distribution of C88 means that CIP has recently requested the acquisition to its genebank (February 2012). Moreover, much of the data associated with C88 reside in difficult-to-access Chinese databases. C88 has the potential to be adopted over a much larger area, being a widely adapted variety, but adoption, and thereby impact, has been severely restricted outside of China.

Summary of CIP contribution to C88
- Joint initiation of the CIP-China potato improvement programme.
- Native potato accessions conserved in CIP genebank that provided the LB resistance.
- Breeding materials derived from native potato clones that contributed to the male parent of C88.
- Substantial evaluation activities to increase adaptation done in conjunction with Chinese colleagues.
- Sponsoring the MSc. thesis work of Chien in the Philippines that involved extensive evaluation of potential male parental material for disease resistance and adaptation.

Counterfactuals and conclusions
There is a very strong link between the CIP genebank and the impact of C88 in south-western China. Without the CIP genebank there would have been relatively little opportunity to produce a new potato variety that was set to have such an impact as C88, given that potato breeding is relatively new in China and that Chinese varieties had a narrow genetic base until the cooperation programme with CIP began. The enhanced LB resistance was largely a product of the genetic traits of the male parent that could only have been bred using CIP expertise, through use of the **unique** diversity represented by a selection of the 4732 native potato accessions in the CIP genebank. Although 15 sources of pollen

contributed to the bulk used in the cross with I-1085, it was important to be able to select from the wide range of potential pollen contributors (that only CIP has). Although it is estimated that only about 5% of CIP's potato germplasm is used by breeders (David Tay, pers. comm.), this does not mean that 95% is redundant: it constitutes the broad genetic base which it is necessary to maintain in order to be able to select suitable material for breeding. It is recognized that CIP's unique native potato collection is likely to represent considerable, but as yet largely untapped, potential for potato breeding in the future. This valuable resource has created substantial interest outside CIP, and is set to make an increased impact in the future.

Although C88 could not have been created without the involvement of the CIP genebank, other improved varieties would have been produced. Indeed they have been, not necessarily with the assistance of CIP or the use of its genebank. China has produced numerous potato varieties through NARS that are grown throughout the country (Thiele et al., 2008), but they are not sufficiently resistant to the major diseases of potato – introduction of new resistance genes was (and still is) needed. The Chinese potato programme, because of the narrow genetic base of its germplasm, would have encountered serious difficulties in managing LB (and other important diseases of potato) through deploying host-plant resistance if it had continued to have resort solely to its own germplasm. The CIP-China cooperative programme has been very productive in this respect. In 1997 CIP-NARS varieties occupied about 127,000 hectares in China while the total potato-growing area was about 3.5 million hectares. Through enhanced co-operation, by 2007 CIP-NARS varieties occupied 448,000 hectares of the total area of 4.8 million hectares (CIP Impact Brief 1, 2009).

LB is the most serious disease of potato worldwide, and developing durable resistance to it is the goal of numerous potato breeding programmes around the world. LB resistance is arguably the most appreciated trait of CIP-related germplasm. It is also an inherently pro-poor trait as it reduces fungicide use and saves capital (Thiele et al., 2010). Jansky et al. (2009), in any case, reported that disease pressure can frequently be severe in Chinese potato fields as use of fungicides is limited or non-existent in most production areas. It would be difficult to calculate the relative costs of developing and maintaining genetic resistance to LB versus fungicide control because LB severity depends greatly on year, site and conditions and is an inherently variable disease that often infects potato along with a host of other serious phytopathogens. However, application of fungicides rather than deployment of host-plant resistance seems currently to represent an unrealistic counterfactual. Moreover, whereas host-plant resistance, exemplified by LB resistance in C88, has no adverse effects on human health or the environment, use and over-use of fungicides certainly impacts negatively on both.

Developing durable LB resistance and producing a high impact potato such as C88 requires extensive genetic resources, necessarily contained in a genebank. It is unlikely to have been the case however that the demise of Mira, which is becoming increasingly susceptible to LB, would have left a gap in the market or that there would have been massive crop failure and famine in China - the world is better prepared than it was when the Irish-European famine occurred in the 1840s through almost total loss of the potato crop to LB. It might be asked whether there would likely have been a change of crop were LB to have become so severe in the absence of resistant varieties (specifically C88). Given the importance of potato to China in terms of industrial processing of coarse starch, expanding production of crisps and French fries, and its value as food (Jansky et al., 2009), it seems unlikely that potato would be replaced by another crop, after all the Irish still grow potatoes despite their 'potato famine' and the United States still cultivates vast areas of maize 40 years after the Southern Corn Leaf Blight epidemic.

There is little doubt that the Chinese potato breeding programme benefitted substantially from access to breeding materials that derived from germplasm in the CIP genebank and CIP knowledge on potato breeding. CIP input resulted in a replacement (to Mira) potato variety being produced sooner than would otherwise have been the case had China been able to get adequately adapted resistant germplasm from elsewhere (which is far from sure). The benefits almost certainly came about

through CIP's international network that allowed LB screening to be done in the highlands of the Philippines and also previous characterization and evaluation work (over many years and sites) that allowed suitable LB resistant clones to be taken directly from the CIP breeding programme (which is based on CIP genebank germplasm) rather than having to have been screened *in situ* to determine the presence of suitable traits. Thus there was a saving of both time and expense in producing C88 through the joint programme.

The maintenance of germplasm in the CIP genebank has a relatively high cost in comparison with, for example, conserving small-grain cereals under dry, cool conditions. The reason is that seed of clonally propagated crops is ideally stored *in vitro*, which requires employing a range of micropropagation/tissue culture techniques. This is particularly the case when virus-free material of normally vegetatively propagated crops has to be maintained. Some CIP material is also maintained as true seed, or is cryopreserved, and there is a field genebank at Huancayo (3200 masl). Full genebanking costs were documented recently (Shands et al., 2010), and a figure of US $1,472,554 was given as the total annual cost of conserving the potato germplasm at CIP (if sweet potato and Andean roots and tubers are included, the figure is about US $3.2 million). An average figure of about US $80 per year represents the cost of maintaining a single potato accession at CIP. Given the economic benefits that accrue from the potato breeding programme at CIP, including C88, these values are very small. Detailed accounts for breeding schemes and activity costs are currently being prepared (pers. comm., Manuel Gastello), but again, the sums involved are small compared with the benefits that derive from the adoption of C88. Knowing these costs might enable the germplasm itself to be assigned a value, but potato breeding is complex, and as already indicated, the value of the germplasm does not reside in specific accessions, but in maintaining (and screening within) a collection representing a wide genetic base. In the case of C88, due to the use of a complex pollen bulk, the precise male donor of the genes conferring enhanced LB resistance is, in any case, not known.

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Appendix-1
Calculation of Economic Surplus from New Variety Adoption

Following Alston, Norton and Pardey (1995) and Fuglie (2007) the estimates of economic surplus derived from new variety adoption are derived from the following expressions:

(4) $\Delta TS = P_0 Q_0 (1-U_s) K (1+0.5Z\eta_a)$

(5) $\Delta CS = P_0 Q_0 (1-U_s) Z (1+0.5Z\eta_a)$

(6) $\Delta PS = \Delta TS - \Delta CS$

with $K = A_T \left(\dfrac{\Delta Y}{\varepsilon} + \dfrac{\Delta C}{P_0 Y_0} \right)$ and $Z = \dfrac{K\varepsilon}{\eta_a + \varepsilon} = (P_0 - P_1)/P_0$

Where:
ΔTS = Total economic surplus
ΔPS = Producer surplus
ΔCS = Consumer surplus
P_0 = Initial market price of the commodity (US \$ t^{-1})
P_1 = Market price of the commodity after adoption (US \$ t^{-1})
Q_0 = Initial market supply of the commodity (t)
U_s = Share of production retained for use as seed (%)
A_T = Expected adoption ceiling (% of area)
Y = Initial average yield (t ha^{-1})
ΔY = Change in yield from adoption of new variety (% of initial yield)
ΔC = Change in production cost from new variety adoption (US \$ ha^{-1})
ε = Price elasticity of supply of the commodity
η_a = Price elasticity of demand (in absolute value) averaged across all uses of the commodity (as food, animal feed, marketed surplus etc.)

In the above equations, U_s is the share of production retained for use as seed, so $Q_0(1-U_s)$ is the net usable production. Z is the price effect measured as a percent change in initial price – and takes a positive value when the price falls. K is a measure of cost savings, as percent of the total value of initial production, resulting from new variety adoption resulting from higher yields and/or lower input use. A good approximation of the changes in total economic surplus as a result of the adoption of the innovation is simply $P_0 Q_0 (1-U_s)K$[14]. The total benefits of adoption (estimated as Area under adoption (hectares) x Benefits per hectare) approximate this measure of economic surplus.

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[14] Fuglie (2007) notes that if $\varepsilon = 1$ and $\eta_a = 0$ then the total economic surplus from the above equation will be exactly equal to $P_0 Q_0(1-U_s)K$. We have used this approximation mainly on account of data constraints. This approximation has been previously used in CIP research assessments (e.g., Walker and Collion: 1997)