Vegetable Crucifers – Status Report

Revised September 22, 2004 by the USDA Crucifer Crop Germplasm Committee
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Vegetable crucifers grown in the United States include a wide array of vegetable crops that span numerous genera and species in the family Brassiceae. These crops range from very specialized niche crops, like arugula, that have minor economic importance, to minor, but mainstream, vegetables like radish, to some of the most economically important vegetable crops such as cabbage and broccoli. A majority of the cruciferous vegetables are minor crops at best and make up a relatively insignificant segment of the vegetable industry. Thus, this crop status report will focus on the primary vegetable crucifers, the cole crops of the species *Brassica oleracea* L., that are widely consumed by the United States public and that contribute most to the agricultural economy of the country.

B. oleracea vegetables have an estimated annual value in the U.S. of over $1 billion (Table 1; summarized from the USDA National Agricultural Statistics Service, 2000; http://www.usda.gov/nass/pubs/estindx.htm). Broccoli is by far the most valuable *B. oleracea* crop with an annual value exceeding $500 million in some years. Cabbage and cauliflower are also high dollar vegetables although less than broccoli. The total value of the *B. oleracea* vegetables as reported by the USDA are conservative, since no statistics are available for kale, collard, or kohlrabi. Some of these less recognized crops are very significant in particular states (e.g., collard is among the top five vegetable crops in South Carolina) and are often cultivated for regional or local markets. *B. oleracea* vegetables are widely recognized as valuable sources of dietary fiber, minerals such as calcium and magnesium, vitamin C, provitamin A carotenoids, and certain glucosinolates that may confer a chemoprotective effect in human consumers.

Table 1. Acreage and dollar value of major *B. oleracea* crops in the USA, 1996-1999.

Crop	Acreage planted (1996-99 range)	Crop value (1996-99 range)
Broccoli	**130,000 – 137,000**	**$416,000,000 - 512,000,000**
Cabbage	**75,800 - 79,600**	**$228,000,000 - 312,000,000**
Cauliflower	**43,700 - 48,400**	**$217,000,000 - 245,000,000**
Brussels sprouts	**3,200 - 3,800**	**$20,000,000 - 22,000,000**

Public Sector Research on Vegetable Crucifers

A significant amount of research is being done in the public sector on this species; however, a majority of this research is best classified as basic genetic research. The most significant and active basic research programs are at University of Wisconsin (Tom Osborn and Richard Amasino), University of California (Carlos Quiros), University of Georgia (Andrew Patterson), and Cornell University (Elizabeth Earle). A smaller program was also initiated at the University of Illinois (Jack Juvik) about five years ago. Of the above programs, all but Earle's are focused on genomics and gene identification. Dr. Earle's program is focused largely on gene transformation and protoplast fusion work.

At present, only three public programs have a significant focus on germplasm and vegetable crucifer breeding. These include a program at Cornell under Phillip Griffiths, one at the USDA-ARS-U.S. Vegetable Laboratory under Mark Farnham, and the third at Oregon State University under James Myers. About 50% of Griffiths' time is dedicated to the vegetable crucifers. He has a significant focus on cabbage, the most important cole crop grown in New York, but he is also conducting research on broccoli and cauliflower. Griffiths has projects looking at host plant resistances to several insects and diseases and is also interested in heat tolerance in broccoli. 100% of Farnham's time is dedicated to vegetable crucifer breeding. He has a strong emphasis on broccoli and smaller efforts on cabbage, collard and kale. He has projects on host plant resistances to different diseases. He is also interested in doubled haploid population development and enhancement of nutritional and nutraceutical properties of the cruciferous vegetables. About 20% of Myers' time is dedicated to vegetable crucifers. His focus is the development of broccoli hybrids for Pacific Northwest processors with improved processing quality traits and suitability for mechanical harvest. He also develops open-pollinated varieties for the home garden trade.

The discovery of phytonutrients (e.g., sulforaphane) in broccoli that promote health in people that consume it has stimulated much interest and research in this crop over the last decade. The number of researchers studying health-promoting characteristics of broccoli is too numerous to list. The lion share of this research, which is being conducted by medical researchers and nutritionists, does not focus on genetics and germplasm issues of the crop. This area of study generally examines the harvested vegetable, seldom taking into account the source of the particular experimental materials.

Private Sector Research on vegetable Crucifers

Over the past ten years there has been considerable consolidation in the vegetable seed industry and this has resulted in a drastic reduction in the number of active commercial breeding programs that breed directly for United States environments. Various programs that used to be conducted by Peto, Asgrow, and Royal Sluis were consolidated under Seminis, and have recently been, for all intents and purposes, eliminated. The only breeding program under the Seminis umbrella that still actively breeds for North America is the broccoli program directed by Gene Mero. One other prominent vegetable crucifer program still being conducted in the United States is the broccoli and cauliflower program at Orsetti Seed directed by Joseph Stern. Two Japanese companies, Sakata and Takii, have very significant market share for seed of several commercial vegetable crucifers. For instance, Sakata's 'Marathon' broccoli has been the industry's standard for more than 10 years and at times has had about 80% or better market share. Although the Japanese companies are big players in the vegetable crucifers, their actual efforts in breeding in the United States are limited. For the most part, cultivars are developed in Japan and then tested in North America for adaptability. Clearly, this has been a successful approach for Sakata especially. Similar to the Japanese, European companies such as Bejo, Ryk Swaan, and Enza Zaden also primarily conduct their actual breeding programs in Europe and only test materials in North America. Although the Europeans have not had the market share like that of the Japanese, they could be poised to claim more, especially in cabbage, with the loss of U.S. breeding programs like the cabbage program recently terminated by Seminis.

Collective Vulnerability of the Cole Crops as it relates to the National Plant Disease Recovery System

There does not appear to be an obvious vulnerability of these crops. The most destructive disease of this species is probably black rot caused by the bacteria *Xanthomonas campestris*. Some chemicals (e.g., copper sulfate) can slow development of black rot, but it is impossible to eradicate the disease with pesticides. Genes conferring some tolerance to black rot were identified and subsequently incorporated into numerous cabbage cultivars, but most cole crops are still quite susceptible to attack by this pathogen. However, if the environment is not conducive to infection (i.e., temperature and humidity are not right), this disease is not likely to present a severe threat. Black rot is a seed-borne disease. If seed crops are infected, seed must be treated before it can be used. This is not a big problem since treatment usually involves hot water (50F) soaking for a short duration (about 10 min). Other serious disease threats to these crops primarily include different fungi that cause downy mildew, alternaria, black leg, and clubroot. Resistances to these diseases have been identified in crop germplasm.

Vegetable crucifers are less vulnerable to insects than they are to diseases. The biggest insect pests of the cole crops include the diamond back moth and a variety of other caterpillars such as the imported cabbageworm, the cabbage looper, the armyworm, as well as others. Numerous pesticides are effective against these pests so control is not a significant issue.

As discussed in the next section, vulnerability varies from crop to crop. For instance, cabbage cultivars exhibit a lot of diversity and the fact that this vegetable is grown throughout different regions of North America would make destruction of this crop on a wide-scale unlikely. There is more vulnerability with a crop like broccoli that is primarily grown in one state (California) and largely represented by one cultivar ('Marathon'). A major epidemic in California of a disease for which 'Marathon' had no resistance could be very damaging to a given crop in a single year. The negative impact of such a crop loss would primarily impact growers. On the contrary, consumers would simply choose other vegetables to consume over broccoli and wait until the supply was available at a later time.

Individual Crop Vulnerability

Broccoli - *B. oleracea*, Italica Group

Currently, up to 90% of U.S. broccoli production is in California. Although production is much less, Arizona and Texas also have significant acreage of this crop. Essentially all broccoli cultivars grown in production in the U.S. are F_1 hybrids that are developed by commercial seed companies. A few open-pollinated cultivars (e.g., Waltham 29) are still available from small seed companies that sell to people interested in growing heirloom varieties and home gardeners interested in relatively cheap seed. Less than five F_1 hybrids probably account for 80-90% U.S. market share for broccoli, and one hybrid, 'Marathon', alone is grown on more than 50 % of the production acreage in the U.S. These varieties have been bred primarily for fresh market, and are not well adapted for (i.e., do not have the traits needed) the processing market. Significant genetic diversity exists among all cultivars still available from seed companies in the U.S., but it is likely that erosion of diversity in this U.S. broccoli germplasm pool will occur as private programs, like the one previously directed by Asgrow, are terminated. This could become a significant concern in light of the fact that the there is a general lack of broccoli in the U.S. Plant Introduction (PI) collection. Although from a dollar value standpoint broccoli is the most important vegetable crucifer in the U.S., only about 5% (89 total) of *B. oleracea* accessions held in the PI system are classed as broccoli or Italica Group.

Cauliflower – *B. oleracea*, Botrytis Group
Currently, up to 90% of the U.S. cauliflower production occurs in California, while Arizona, New York, Texas and Michigan produce significant, albeit much smaller cauliflower crops. Among cauliflower cultivars, some are best classified as highly inbred and uniform, self-pollinated populations, while more and more are actually F_1 hybrids. Previously, a lack of useful self-incompatibility alleles in cauliflower limited development of F1 hybrids. However, identification of more useful alleles and the advent of genetic and cytoplasmic male sterility have stimulated more cauliflower F1 hybrid development in the last decade or so. As with broccoli, significant genetic diversity exists among all cauliflower cultivars still available from seed companies in the U.S., but erosion of this diversity will increase as private programs, like the one previously directed by Royal Sluis, are terminated. This may not be as critical as it is with broccoli since cauliflower has better representation in the PI collection wherein about 20% (352 total) of *B. oleracea* accessions held in the system are classed as cauliflower or Botrytis Group.

Cabbage – *B. oleracea*, Capitata Group
U.S. cabbage production is more widely distributed than other cole crops. California and New York are the two biggest producers with about 12,000 acres each in 1999, but Florida, Georgia, North Carolina, Texas, and Wisconsin all have more than 5,000 acres of cabbage. Almost all cultivars grown for commercial production are F_1 hybrids, although open-pollinated cultivars (e.g., Golden Acre) are still available from small seed companies that sell to people interested in growing heirloom varieties and home gardeners or small producers interested in relatively cheap seed. Numerous market types (e.g. fresh market, processing, storage, etc.) of cabbage stimulate greater genetic diversity among cultivars grown and help to insure maintenance of diversity by seed companies. However, a likely erosion of diversity in the U.S. crop will also occur due to the loss of seed company programs. Of all cole crops, cabbage has the best representation of all crops in the PI collection. About half (800-900) of all *B. oleracea* accessions are classed as Capitata.

Collard – *B. oleracea*, Acephala? Sabellica? or Capitata Group?
Collard is a cole crop that is deemed uniquely American. It was likely brought to North America by British colonials and subsequently flourished in the southeastern U.S., but specifics of its beginnings are not readily available. Although collard is often classified in the Acephala Group with kale, it is more likely that collard was selected as a nonheading cabbage out of traditional heading cabbage types that have been cultivated in the Southeast since colonial times. This crop is relatively minor compared to broccoli, cauliflower or cabbage, and no statistics are compiled for it by the USDA. However, it is among the top 5-10 vegetable crops in most southeastern states. Since collard production in South Carolina alone entails more than 5,000 acres, this crop is easily more significant than that of Brussels sprouts for which the USDA compiles statistics. Commercial seed companies have minimal interest in this cole crop and less than10 cultivars are presently available to producers. These cultivars include about four F_1 hybrids and several open-pollinated populations. One hybrid, ‘Top Bunch’ is probably the most widely grown cultivar, while the hybrid ‘Blue Max’ also has significant market share. Although the number of available cultivars is small, studies have

shown there is significant genetic diversity within the old open-pollinated populations sold as cultivars. In addition, evidence indicates there is additional diversity contained in collard landraces still in existence and mostly grown in small gardens or farm plots in the southeastern states. It is likely that this diversity in landraces will be lost in another generation as the southeast continues to be developed and more farmers and rural populations leave the land for larger communities. Until recently, there were no collard accessions in the PI collection.

Kale – *B. oleracea*, Acephala Group
No USDA production statistics are available for kale, but acreage of this crop has grown dramatically in the southeastern U.S. Direct knowledge of kale production in the Southeast indicates that U.S. production of this crop entails more acreage than used for Brussels sprouts. Production of kale is more widespread, similar to cabbage, and the primary use of this crop is for garnish on restaurant salad bars. At present, less than 10 cultivars are available in the U.S.; these include three to four F_1 hybrids and several open-pollinated populations. As with collard, significant genetic diversity exists within open-pollinated populations used as cultivars. New diversity in this crop is not likely to be found in the U.S. and to date there is nothing in the PI collection classified as kale or Acephala Group.

Brussels sprouts – *B. oleracea*, Gemmifera Group
The vast majority of U.S. Brussels sprouts production is in California. Little information is available for production of this crop in other states. Most commercially grown cultivars are F1 hybrids and few are available for sale in the U.S. Little is known about genetic diversity in this crop although it is likely more limited than with other cole crops. There is limited representation of this crop in the PI collection with less than 5% (76 total) Gemmifera accessions among all *B. oleracea* in the system.

Other Vegetable Crucifers
There are many other vegetable crucifers that are considered minor vegetables. Among these crucifers are vegetables such as: radish (*Raphanus sativa* L.); mustard greens (*B. juncea* L., *B. nigra* L., or *B. rapa* L.); turnips, Chinese cabbage, and pak choi (*B. rapa* L.); arugula (*Eruca sativa* L.); and others. Small and niche markets for some of these vegetables occur throughout the U.S., but there significance does not approach that of the above-described *B. oleracea* vegetables. Little expertise on genetics and breeding of these crops is available in the U.S. with a majority of cultivars for these vegetables being developed in foreign countries. Significance of some of these vegetables is likely to increase over time as popularity increases.

Germplasm Needs

Regeneration, Maintenance and Preservation. The most critical need for management of the vegetable crucifer collection held by the USDA is regeneration of old seed lots that exhibit poor germination. The Crucifer Crop Germplasm Committee recognizes that the current curator, Dr. Larry Robertson, of the vegetable accessions held at Geneva, NY has made significant progress in the last five years (his tenure at Geneva) in regenerating accessions under his control. However, it is evident that Dr. Robertson inherited a collection that had been neglected for some time. Reports from Dr. Robertson indicate that some vegetable crucifer accessions have been essentially lost due to zero seed viability. Therefore, immediate action over the next few years remains to regenerate lots with low germination before additional accessions are also lost. After that, it will be advantageous if a regular schedule for regeneration of accessions is put into place so this collection does not undergo deterioration in the future.

Collection. An effective way to increase diversity in the USDA vegetable crucifer collection would be by obtaining accessions from foreign gene banks for inclusion in the U.S. system. The Europeans, in particular, have very good collections of vegetable crucifers and selective requests from some of these collections [i.e., one held by Horticulture Research International (HRI) at Wellesbourne, UK] could effectively fill gaps in the USDA collection for specific crops. As an example, broccoli is lacking in the U.S. PI collection, but HRI has an extensive collection of this crop group. If some of these broccoli accessions were input into the USDA collection, they would enhance USDA broccoli holdings significantly. The amount of seed for a given accession that can be obtained from a gene bank would of course be limited, so once a small seed lot was obtained for inclusion in the USDA collection, it would be necessary to regenerate it to increase seed stocks.

One collection previously recommended and that is now underway is to locate and obtain landraces of collard in the southeastern U.S. Putative collard landraces have been saved for many generations and it is likely that such landraces are highly adapted to southeastern conditions, possibly expressing resistances to disease or insect pests prevalent in this region. Mark Farnham and colleagues Ed Davis and John Morgan, at Emory and Henry College in Virginia, are presently seeking collard accessions in coastal North and South Carolina. They have collected more than 40 samples to date and will continue this exploration for one or two more years. It is important that this collection activity be done now since there is a high likelihood that many of these collard landraces will be lost within the next generation. Most samples obtained in the last year are from individuals more than 70 years of age.

Evaluation. Although regenerating the vegetable crucifer collection and increasing diversity in this collection by obtaining new accessions have higher priorities, evaluation needs of the collection still exist. In general, there is a lack of basic phenotypic information regarding most cole crop accessions in the PI collection. Recently, phenotypic data (including digital images) were gathered for more than 400 Capitata accessions and this data should prove useful to individuals that may wish to use these accessions in the future. Additional phenotypic characterizations of additional cabbage accessions as well as other crop accessions are recommended. A characterization of the vernalization requirements of accessions, especially cauliflower and broccoli, would be very useful. Usefulness of this information is emphasized by the following example. If one is interested in head characteristics of accessions and grows these plants without a cold or vernalizing treatment, accessions that require such a treatment will not be vernalized and fail to produce heads. In this scenario head evaluation is impossible.

Enhancement. Enhancement of materials in the PI collection is a low priority issue. Private companies in the U.S., Europe, and Asia are working to enhance most important cole crops through systematic genetic improvement. In addition, individual public programs like those at Cornell University and the U.S. Vegetable Laboratory are actively working to improve particular and economically important traits (e.g., disease resistance) in the these crops. Actual enhancement efforts are best left to these public and private entities at the present.