THE VALUE OF HERBICIDES IN U.S. CROP PRODUCTION

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1.0 Introduction

Herbicides for weed control represent 60% of the volume and 65% of the expenditures for all pesticides used by U.S. farmers (see Table 1). Widespread herbicide use is a relatively recent development in U.S. agriculture in comparison to insecticides and fungicides that were routinely used in inorganic chemical formulations on U.S. fruit and vegetable acreage beginning in the early 1900s. By contrast, widespread use of herbicides to kill weeds did not begin until the development of synthetic organic chemicals in the late 1940s. Currently, herbicides are routinely used on more than 90% of the acreage of most U.S. crops. Herbicides substituted for laborers hoeing weeds out of fields and reduced the need for cultivation of weeds with mechanical equipment. The period following the rapid adoption of herbicide technology was characterized by large increases in crop yields in the U.S. Although a voluminous literature exists that documents the contribution of herbicides in improving yields and reducing grower costs, no single reference source has been assembled that quantifies the impacts herbicides have made in U.S. agricultural production. This report documents for 40 crops the changes in crop production and economic returns following the widespread adoption of herbicides to control weeds in the U.S.

This report estimates the total expenditures on herbicides and their application currently made by U.S. farmers and determines the value of that expenditure in terms of higher yields and lower costs in comparison to the likely alternatives to herbicides. This report estimates the economic value of herbicides by simulating the impacts of their nonuse. There are nonchemical methods for weed control, and this report estimates their use as replacements for herbicides for the 40 crops selected for study. Essentially, this question is answered: What would be the likely economic effects if U.S. farmers did not use herbicides? Answering this question has relevance because of three current developments:

- <u>Organic Agriculture</u> Organic farmers do not use herbicides and routinely report that weed control without chemicals is their biggest problem and cost. Considerable information on the economics of weed control in organic production is included in this report. By estimating the impacts on U.S. farmers not using herbicides, the implications of a potential widespread conversion of U.S. agriculture to organic methods are quantified.

- Regulatory Policies Herbicides are heavily regulated by federal and state agencies. The costs of regulation have increased significantly, and fewer new herbicides are being registered in the U.S. Older herbicides are also undergoing regulatory scrutiny, and many registered uses may be withdrawn by manufacturers or cancelled by regulatory agencies. Quantitative examples of the impacts on farmers when there are no effective herbicides registered for their use are included in this report. By estimating the impacts of U.S. farmers doing without herbicides, the economic effects likely to result if regulatory actions lead to widespread cancellations of the registered uses of herbicides are quantified.
- Weed Resistance Recently, there has been considerable media attention to the potential development of "superweeds" that would be resistant to all herbicides. This issue has emerged as part of the scrutiny of genetically engineered herbicide tolerant crops and the potential for gene flow to weeds that could gain resistance. There are numerous examples in the U.S. of specific weed species that have developed resistance to individual, and even multiple, classes of herbicides. By estimating the impacts of U.S. farmers doing without herbicides, the likely impacts if widespread weed resistance develops rendering ineffective the herbicides currently used in U.S. agriculture are quantified.

It is highly unlikely that U.S. growers will have to do without their use of herbicides in the foreseeable future. It is highly unlikely that regulatory agencies will prohibit herbicide use on a large scale, and it is equally unlikely that weed resistance problems will render herbicides ineffective for all crops. Thus, this report is meant solely to provide a means of estimating the economic value of a technology. Nevertheless, this report should be of interest to policymakers, regulators and legislators whose decisions and rules will affect the future availability of chemical herbicides. The report should be of interest to the media and the public as they follow ongoing issues such as the development of genetically engineered crops and the promotion of organic farming.

Table 1
Pesticide Use and Expenditures: U.S. Agriculture (1999)

	Volume %	Expenditures %
Herbicides	60	65
Insecticides	14	18
Fungicides	6	9
Other	20	8
Total	100	100

Source: USEPA [125]

2.0 Background

A. Weeds

Weeds are plants growing where they are not wanted. Weeds compete with crops for moisture, nutrients, sunlight and space thereby resulting in significant crop losses. Weeds deprive crop plants of natural resources. For example, a corn plant requires 368 pounds of water to produce one pound of corn, whereas weeds such as lambsquarters and ragweed use 800 and 950 pounds of water, respectively, to produce a pound of dry matter [148]. One cocklebur may occupy four to eight square feet of soil surface area, thereby reducing the space available for crop growth. When weeds shade crop plants, less sunlight is available for crop production.

Natural weed populations in most fields are high enough to cause devastating yield losses in most crops if not controlled by some method [279]. Loss figures of 50-90% are not uncommon for crops grown in natural weed infestations [277] [278]. Yield losses depend on the competing weed species and its density. Corn yields were reduced 10% by giant foxtail, 11% by common lambsquarters, 18% by velvetleaf and 22% by common cocklebur at a density of only two plants per foot of row [45].

Weed seeds present in harvested crop can cause rejection of the crop by processors. For example, presence of nightshade or morningglory seed, similar in size, shape and color to pea or lima bean, leads to refusal of whole harvested loads. Weeds harvested with crops like mint and spinach lead to product contamination and off flavors, which result in lower prices for farmers.

Weeds are different from other pests that pose problems in crop production. Weeds are less transient and less difficult to predict than other crop pests. Weed populations in crop fields are relatively constant while outbreaks of insect and disease pathogens are sporadic.

There are several characteristics that set weeds apart from crop plants. Weeds germinate over a wide range of environmental conditions and have faster rates of development due to high food production efficiency compared to crop plants. These characteristics offer physiological advantages to weeds over crop plants. Weeds typically are able to produce seed before the crop is harvested, are self-pollinated, and have long periods of seed production. Moreover, weed seeds are excellent travelers. Many possess special adaptations such as hooks, wings and spines that aid in their long and short distance spread by wind, water, livestock, human beings or farm equipment.

Two other factors that contribute to the strong competitive nature of weeds include high seed production, leading to high population density and survival in the soil [272]. Weed species re-infest the soil primarily due to the large amounts of seeds produced by a single plant. Table 2 lists the number of seeds produced per plant by several weed species of importance to U.S. crop production. For instance, seed production of individual redroot pigweed, common ragweed and lambsquarters can be as high as 117,400, 3,380 and 72,450, respectively [273].

The high fecundity of weeds has contributed to the millions of buried weed seeds in a typical acre of cropland in the U.S. In Minnesota, weed seed counts at four different locations in 24 different plots varied from 98 to 3068 weed seeds per square foot of soil six inches deep – that converts to 4 million to 133 million seeds per acre [272]. In western Nebraska, average cropland soil contained 200 million seeds per acre [274]. In a similar Colorado experiment, 122 million weed seeds per acre were present in the upper 25 cm of the soil profile [346]. In California vineyards, counts of 40 million weed seeds per acre have been estimated [412]. In Iowa, the average weed seed counts ranged from 113 million to 613 million seeds per acre [413].

The number of weed seeds that germinate and emerge in any given year is quite low in relation to the total number of seeds present – perhaps only 5-10% of the total seed population [275]. A very high percentage of the total weed seed population in the soil survives from one year to the next. Seed longevity represents a major survival mechanism for weed species; it constitutes a continuing source of emerging weeds in croplands [273]. Table 2 lists the length of survival in soil of several common weed species in U.S. crop fields. The seeds of these species can survive in the soil for decades. A typical population of emerged weeds in cropland is approximately 2.5 million weeds per acre.

An experiment was started in 1902 at the Arlington Experimental Farm, Rosslyn, Va., to determine the longevity of seeds buried in the soil under natural conditions. This experiment was terminated in 1941 when the site was occupied by the U.S. War Department [370]. A large percent of the seeds buried in 1902 germinated when dug up in 1941: velvetleaf (48%), morningglory (31%), jimsonweed (91%), black nightshade (83%) and ragweed (22%) [370] (see Table 2).

On the basis of life duration, weeds are classified as annuals (winter or summer), biennials and perennials. Annual weeds complete their life cycle in one growing season only. While summer annuals (e.g. lambsquarters, ragweed, morningglory, pigweed) germinate in spring, produce seed in summer and die in fall, winter annuals (e.g. chickweed, shepherd's-purse, redstem filaree, annual bluegrass) germinate in late summer, go dormant during the winter, produce seed in spring and die in summer. Seeds of biennial weeds germinate in spring, summer or fall of the first year, overwinter with a storage root and rosette leaves and flower and produce seed in winter of the second year upon exposure to cold. Perennial weeds, by definition, survive for an indefinite number of years and produce new aerial stems each year from underground roots and stems. Perennial weeds often have extensive root systems and reproduce by both vegetative (e.g. tubers, rhizomes, stolons, suckers) and sexual (seed) means. In addition, perennial weeds have the ability to propagate and regenerate from pieces of stems and roots. Therefore, they are the most difficult to control weeds in field crops. Some examples of perennial weeds are horsenettle, Canada thistle, Johnsongrass, nutsedge, and bermudagrass.

The life cycle of weeds starts with seed germination and emergence followed by vegetative development and competition and ending in the reproductive phase and seed production. Weed seeds remain dormant or inactive in the soil until conditions are right for germination. Germination requirements of weeds and crop are typically similar. Four factors affect the dormancy and germination of weed seeds: soil temperature, moisture, oxygen and light. The soil temperature requirement of weed seeds varies between species. For example, summer annuals require 65^0 to 95^0 F to germinate while winter annuals need comparatively low temperatures between 40^0 and 60^0 F [272].

Moisture availability is a major factor that determines the onset of germination. Moisture activates enzymes needed to break down the stored food, increase respiration and activate cell division at growing points. Some weed species germinate over a large range of water tensions while germination in others occur only at a specific water tension. Most weed seeds need moisture content of at least 14% of their weight to initiate germination [272]. Weed seeds remain dormant if the desired moisture levels are not present.

Soil oxygen levels needed for germination differ between cropping systems. Soil oxygen levels are 8 – 9% in corn but are less than 1% in rice [272]. Soil oxygen is lower in rice fields due to the maintenance of flood conditions to prevent weed germination and growth. Therefore, weeds in a rice cropping system are adapted to germinate at lower oxygen levels than the weeds in upland crops. Germination of most weed seeds is sensitive to light and does not occur in non-ideal conditions such as shade provided by the crop canopy. Upon exposure to specific environmental cues, weed seeds germinate in flushes. The time of this flush varies by species and the prevailing environmental conditions. Some species may have more than one flush per season. The first flush of germinating weeds usually originates from the top 1 – 4 inches of soil depth [273]. In addition to germinating in flushes, some weeds germinate throughout the crop season.

Weed species differ in the time of first emergence and the length of emergence. Weeds such as giant ragweed and woolly cupgrass are characterized as early emerging while pigweed and crabgrass are late emerging. Some weeds, such as wild radish, have adapted sporadic germination patterns to survive control measures [272]. However, a small percent of all weed species emerge throughout the season. Early emerging weeds are a major threat to crop production, as they are the most competitive and produce the most seed. The survival of late emerging weeds is usually low due to shading by crop. Even though few and with no impact on crop yields, late emerging weeds are still a concern because of their contribution to soil seedbank.

The struggle for existence between weed and crop plants generally starts at an early stage (seedling stage). Soon after emergence, weeds interact with nearby plants, either with other weeds or crop, and vie for the shared growth resources (light, soil moisture, carbon dioxide, nutrients and space). The mutually adverse effect of weeds and crop that utilize limited resources is called competition. In other words, the competitiveness of a plant is its relative ability to obtain a specific resource. If weeds are able to compete for and utilize a sufficient amount of some growth factor to the detriment of the crop, the result is an adverse impact on crop yield.

Crops vary greatly in their ability to compete with weeds. Vegetable crops such as onion and pea, in general, are poor competitors while agronomic crops such as corn and soybean are good competitors. Broadleaved weeds in general are more competitive than grass weeds. This is because of the greater leaf area of broadleaf weeds, which aids in higher light interception. For instance, common cocklebur, an important weed in soybean production, reduced yields by 80% at a density of nine plants/square meter whereas yield reduction from less competitive giant foxtail was 10% from six plants per square meter [276]. Weeds that emerge prior to or along with crop exert the most effect on crop yield than the ones that emerge later.

For most crops, it is critical that fields are kept weed-free during the first four to six weeks after planting to prevent serious yield losses from early season weed competition. The critical period for weed control results from the effects of weed competition not being uniform throughout the year. Rather, yield reduction occurs only during certain, typically brief, stages of crop growth. Weeds must be controlled during this time. Research has shown that soybean fields should be kept weed-free four to six weeks after planting [276]. Any weed emerging in the crop after this initial weed-free period will not compete effectively with soybean and will not affect yield potential due to the soybean canopy, which shades the emerging weeds. For a sweet corn variety maturing in 10 weeks, this critical period occurs from week two to week five. This means that weeds emerging during the first week will not cause corn yield reductions if they are removed before the fifth week. Weeds emerging after the fifth week will not result in yield reduction if not controlled [271].

Critical periods of crop-weed competition vary depending on crop, weed, weather, growing conditions, soil type and tillage. Critical weed-free period for horticultural crops such as snap bean usually occurs sooner and stays longer than for agronomic crops, mainly due to the poor competitive ability of horticultural crops. Environmental conditions may affect weeds and crop differently each year and could affect the length of critical weed-free period. The critical weed-free period concept does not mean that weeds can be ignored except during the critical period. It merely helps determine when it is necessary to undertake control measures to avoid yield losses. Weeds present after the end of the weed-free period may not reduce yield but can make harvest difficult and contribute to the soil seedbank.

A large number of weed species infest crop fields in the U.S. However, only two to four species typically dominate the weed population in a field [274]. In a typical field in the Midwest, weed control strategies are generally planned based on two grass weed species and three to five broadleaf species. Table 3 lists important weed species infesting selected crops in major producing states. This Table shows estimates of the percentage of crop acreage in each state infested with each species. Some species are very common – infesting more than 90% of the acreage while other species infest a much smaller area. A combination of broadleaf and grass weed species infest a sizable portion of the acreages in all states. Table 3 also contains estimates of the potential impacts on crop yields of uncontrolled populations of each weed species in each state. Some weed species are very competitive and would reduce yields by more than 80% if not controlled while other weed species are less competitive and would likely reduce yield by 5% if not controlled.

B. Tillage

One of the primary reasons for growing crops in rows was to allow the passage of cultivation equipment pulled by draft animals. Row widths were dictated by the minimum distance needed for the draft animal. Many types and sizes of tillage equipment are available: harrows, cultivators, tandem disks, rotary hoes and the moldboard plow.

Cultivation is used to control weeds either prior to planting the crop or during the crop growth season. Weed control by the tillage method is achieved primarily by 1) the burial of small annual weeds in soil thrown over them through the action of tillage tools and 2) the disruption of the intimate relationship between the weed plant and the soil, whereby a) the soil is loosened about the roots, resulting in disruption of water absorption and death by desiccation, or b) the plant is “cut off” below ground. Pre-plant tillage helps in weed management by cutting the existing weeds loose from soil and breaking them apart, burying the weed seeds in deeper soil layers to prevent them from germinating, and bringing the weed seeds to soil surface to trigger germination as a means to control them. In-crop cultivation kills the weeds between crop rows by cutting the plant tops from roots and burying them leading to desiccation and depletion of food reserves. Cultivation is most effective at seedling stage (before secondary root formation) of weeds as this stage has no food reserves and is vulnerable to root disturbance. Cultivation is not effective in controlling the weeds in crop rows because of potential crop injury. Cultivation is less effective in controlling perennial weeds as they quickly sprout from the underground roots, tubers or rhizomes. Rather than controlling these weeds, cultivation can spread them by dragging the self-propagating structures such as rhizomes along the rows.

Best results from cultivation are obtained with small (< 2.5 inches) weeds. Large weeds are difficult to bury and have sufficient roots to escape total separation from the soil. Cultivation equipment can also be clogged by the larger weeds. Effective cultivation needs dry soil both at the surface and below the depth of cultivation. Dry soil promotes desiccation of the uprooted weeds. Proper soil moisture for working the ground will also avoid damage to soil structure. Cultivation while the soil is too wet will simply transplant weeds, especially the vegetative reproduction organs of perennial weeds. The same problem can occur if rainfall occurs soon after cultivation. Ample moisture in the soil will promote weed survival after cultivation [272].

The criteria for optimal weed size and soil moisture are two limitations to the use of cultivation for weed control. These can be especially critical if cultivation is used as the sole means of weed control. Untimely rain that delays the use of cultivation can result in large uncontrollable weeds [272].

Surveys of farmers who have stopped cultivation in preference to herbicide use indicate that farmers reject cultivation because it is too time-consuming and intrusive into other needed work [414]. Cultivation of large acreages requires continuous weeks of effort, which is particularly burdensome on farmers who use little or no hired help. Effective cultivation also creates an unwanted dependency on the weather. In years with a particularly wet spring and early summer, cultivation has to be postponed, which means farmers lose control over the timing of their operations [414].

C. Herbicides

Herbicides are chemicals that kill plants. Plants are complex organisms in which multitudes of vital processes take place in integrated sequences. Some of these vital metabolic plant processes include photosynthesis, amino acid and protein synthesis, lipid synthesis, pigment synthesis, nucleic acid synthesis, respiration, cell division and maintenance of membrane integrity. Herbicides injure and kill plants by interfering with the normal function of one or more of these vital processes. This ability of herbicides to kill certain plants without causing any effect on other plants is called “selectivity”. Herbicides that kill most plant species are called nonselective herbicides. Herbicides such as 2,4-D, fomesafen and triclopyr are phytotoxic to broadleaf weeds while clethodim and sethyoxydim are toxic only to grass weeds. Selective herbicides do not injure crop but are toxic to weeds only.

Crop plants escape the toxic effects of herbicides through physical or biochemical mechanisms. Physical methods of selectivity are based on the difference in volume of herbicide retained by crop and weed plants. These differences arise due to crops and weeds having different leaf arrangements, leaf angles or surface wax properties. Biochemical selectivity stems from reduced herbicide uptake, rapid degradation, deactivation or metabolism of the chemical. Wheat and other grass crop plants (corn, rice) tolerate 2,4-D and MCPA because they can metabolize these herbicides faster than broadleaf plants. When atrazine is applied for weed control in corn, corn plants deactivate atrazine by binding to naturally occurring plant chemicals. Similarly, soybean tolerance to metribuzin is partially due to the deactivation of the herbicide by binding to plant sugar molecules. Susceptible weeds either cannot metabolize the herbicide or metabolize it too slowly for detoxification.

Herbicides are grouped based on how they kill the plants (termed as mode of action), timing of their application and chemical structure. Herbicides are contact, translocated, or soil applied depending on their mode of action. Contact herbicides are those that do not readily translocate in the plant. As a result, contact herbicides such as glufosinate cause only localized injury at the point of contact on plants. On the other hand, translocated or systemic herbicides such as glyphosate and 2,4-D move within the plant system along with food or water. Referred to as residual herbicides (e.g. trifluralin, s-metolachlor), soil applied herbicides are the ones which need to be absorbed by roots or emerging shoots.

Timing of herbicide treatments depends on several factors: herbicide used, its persistence, weed characteristics, weather and soil conditions. Based on the time of application, herbicides are classified as preplant, pre-emergence (PRE), or post-emergence (POST) herbicides. While preplant applications refer to herbicide treatments made to soil prior to planting the crop, PRE herbicides are the ones applied after planting but before crop and/or weeds have emerged. Both preplant and PRE herbicides need to be moved to the top 1 inch to 3 inch soil depth by mechanical incorporation or rainfall to be active against the germinating weed seeds. The majority of weed seeds germinate from the top 1 to 2 inches of soil surface. POST herbicide applications are made following the emergence of weed and/or crop.

Weed control with PRE herbicides provides crop with a competitive advantage due to the control of weeds early on. Pre-emergence herbicides remain active in the soil for an extended period of time, thereby providing residual control of weeds. In orchard crops, pre-emergence herbicides can stay active for six months. Seedlings of germinating weeds that come in contact with PRE herbicides absorb the chemical through roots or shoots resulting in phytotoxicity.

POST herbicides are usually applied when weeds are growing actively. A compound called "surfactant" may be added to POST sprays to enhance the performance of the herbicide. The surfactant improves the coverage of the herbicide on leaves by reducing the surface tension of the spray droplets and allowing greater pesticide contact. Post-emergence herbicides need a specified drying time for maximum effectiveness (rainfast period). Rainfast period is the length of time that needs to pass after herbicide application before an irrigation or rainfall event to ensure that plants had enough time to absorb the herbicide. Rainfast period differs between different herbicides (2 min for lactofen versus 2 hr for glyphosate).

Herbicides that are chemically similar usually produce the same type of physiological reaction in plants and control similar species. Therefore, herbicides with a common chemistry have been organized into families. Herbicide families, based on how they kill plants (mechanism of action), are grouped as amino acid synthesis inhibitors, cell membrane disruptors, growth regulators, lipid synthesis inhibitors, pigment inhibitors, photosynthesis inhibitors and seedling growth inhibitors. Generally, individual crops are treated with two to three herbicides. For example, separate herbicides may be used pre-emergence to control the major broadleaf and grass weeds infesting a crop. Additional herbicides may be used post-emergence to control emerged weeds that are missed by the pre-emergence application.

D. Historical

In the early years of crop production in the U.S., human labor was used to remove weeds from fields. As late as 1850, 65% of the U.S. population lived on farms and removing weeds was one of the main farm chores [415]. The development of machinery powered by animals and tractors made mechanical cultivation of weeds possible. A common recommendation for control of perennial weeds was to fallow a field for a year and cultivate it 12-14 times [415]. Certain weed problems received congressional attention. In 1901, Congress appropriated funds to research control of Johnsongrass. In 1935, Congress appropriated funds to research the control of field bindweed, a perennial that was rapidly spreading across the Midwest and west. Bindweed infestations had resulted in substantial acreages of productive wheat land being taken out of production in the northwest [415]. In Kansas, some loan companies refused to accept mortgages on farms infested with bindweed [417].

It had been known for centuries that certain materials, such as salt, would kill plants if applied at heavy rates; however, it left the soil unusable for a period of time [415]. Salt was extensively used to kill bindweed in Kansas. Salt was applied at a rate of 20 to 25 tons per acre in a layer about one fifth of an inch thick [417]. A few plants would still come up and had to be treated the following year. Salt was used extensively on railroad and highway rights of way [416]. However, since it left the soil barren for an extended period of time, it was impractical for cropland. One two-acre field in Kansas was still barren 17 years after being salted [417]. In Kansas between 1937 and 1947, farmers applied 16 million pounds of sodium chlorate, 120 million pounds of sodium chloride and two million pounds of borax for control of bindweed [375].

In the early 1900s, research was conducted with copper, iron and arsenic for potential in weed control [416]. These inorganic chemicals burned or poisoned the plant tissues, killing those parts of the plant that they touched directly. Several of these inorganic compounds were used extensively to control weeds in non-cropland areas such as along rights of way and irrigation ditchbanks, but were not used in agriculture. Farmers showed little interest in inorganic chemical weed killers. They found that treatment required large quantities of the chemicals with a resulting high cost-per-acre. Further, the frequently toxic, flammable or corrosive chemicals seldom killed weeds effectively or consistently [411]. Beginning in 1919, oils and kerosene were increasingly used to control weeds in non-cropland areas and also found some uses in crops that tolerated their use: citrus, cranberries and carrots [416].

At the time the federal-state research program on field bindweed was initiated (1935), there were six full-time federal weed researchers in the U.S. and not more than ten to twelve state experiment station workers in the U.S. These workers were spending one-tenth to one-third of their time on weed research [416]. In contrast, there were more than 500 full-time federal and state experiment station workers in each of the fields of entomology and plant pathology [416].

Between 1880 and the mid 1930s, several botanists pursued a different line of investigation that made possible the discovery of herbicides. Botanists had long been intrigued with plant shoot and root growth and the mechanisms causing plants to respond to stimuli [393]. Plant physiologists also found that some chemicals induced rooting, hastened the ripening and coloring of fruits or even produced seedless tomatoes. Workers had noted that too large an amount of a growth regulator injured plant tissues. Distortion of various parts of the plant was common; sometimes the overdose even killed the plant. When this occurred, the scientists merely tossed the dead plants aside [411].

In the early 1940s, some researchers began to test a new plant regulator chemical compound for herbicidal activity. The chemical was 2,4-dichlorophenoxyacetic acid (2,4-D). Public researchers in the 1942-1944 time period tested 2,4-D as an herbicide and reported success in killing field bindweed with the chemical. 2,4-D was tested on lawns and golf courses with the result that broadleaf weeds were killed with no injury to the lawn or turf grasses. The articles about field bindweed stimulated interest by regulatory agencies with bindweed eradication programs. USDA ordered human toxicity studies in 1945, which proved negative. The first year of widespread testing and sale of 2,4-D in the U.S. was 1945, and 917,000 pounds were produced. Production rose to 14 million pounds in 1950. 2,4-D proved useful to selectively control broadleaf weeds without harm to grass crops (wheat, corn, rice) [411].

Significant plant research with chemicals was carried out in secret during World War II by the U.S. Army at Camp Detrick, Maryland. The research was focused on the testing of chemicals for destroying crops. All of the research at Camp Detrick was kept under military secrecy until the end of World War II. The entire June 1946 issue of the *Botanical Gazette* consisted of papers from Camp Detrick scientists. Among the accomplishments of the Camp Detrick scientists were the development of methods for evaluating over 1,000 chemical compounds for their herbicidal properties, defining the selective action of sprays on broadleaf plants, identifying the herbicidal effects of soil and water applications and determining the dosages required [393].

Chemical companies appreciated the value and potential of the market for herbicides; by 1947 they had placed 30 different preparations of herbicides containing 2,4-D on the market. In 1949, they marketed 20 different kinds of systemic organic herbicides. These included chemicals tested at Camp Detrick, such as IPC, which killed grasses without harming broadleaf crops. By 1962, companies marketed about 100 herbicides in 6,000 different formulations. Increased specificity for particular weed problems in individual crops under different soil and climatic conditions accounted for this increased development of products [411]. Within 2 years of the introduction of 2,4-D, the acreages in the Northwest that previously had been heavily infested with bindweed were brought into wheat production [415].

The discovery of 2,4-D and the resultant publicity provided the stimuli that started weed research on its way as a new science. Weed research suddenly became popular and many scientists became interested in studying the impacts of chemicals on weeds and crops. Calculations were made as to how many weeds could be killed at what cost using herbicides. For example, one estimate was that for 50 cents (the cost of one pint of 2,4-D) a spray operator could kill 20 million weeds in an hour [353]. This estimate was based on spraying ten acres in one hour and an infestation of 50 weeds per square foot. Many thousands of chemicals were screened and many hundreds were tested [416]. Funds for weed control research at ARS and at state experiment stations increased from $800,000 in 1950 to $4.6 million in 1962 [416]. By 1962, the number of federal and state weed research workers had increased to the equivalent of 246 fulltime workers [416].

State and regional weed control conferences had been organized in the 1930s and 1940s. In 1949, the Association of Regional Weed Control Conferences was organized. It initiated the first scientific periodical devoted to weeds in 1951- *Weeds* - and organized the first joint weed meeting in 1953. The Weed Society of America was organized in 1954 and held its first meeting in 1956. The Society, now the Weed Science Society of America adopted *Weeds*, now *Weed Science*, as its official journal.

University weed science researchers have played an important role in the testing of new herbicides for efficacy and crop safety. These scientists have been responsible for making recommendations to farmers in their states regarding the cost-effectiveness of available weed control strategies and for conducting research into possible weed control methods for use in controlling the most troublesome weeds facing growers.

Table 2: Weed Seed Production and Length of Seed Survival in Soil		
Weed Species	# of Seeds Per Plant	Length of Survival in Undisturbed Soil (Years)
Common Cocklebur	900	8
Common Lambsquarters	72,450	39
Common Ragweed	3,380	39
Green Foxtail	34,000	39
Pennsylvania Smartweed	19,300	30
Redroot Pigweed	117,400	10
Velvetleaf	2,000	10

Source: [274]

Table 3: Weed Species Infestations By State and Crop (Selected Species Only)

State	*Crop*	*Species*	*Acreage Infested*	*% Potential Yield Loss*
ALABAMA	COTTON	COCKLEBUR, COMMON	48	85
ALABAMA	COTTON	CRABGRASS, LARGE	43	60
ALABAMA	COTTON	SICKLEPOD	20	45
ALABAMA	SWEET POTATOES	COCKLEBUR, COMMON	20	70
ALABAMA	SWEET POTATOES	CRABGRASS, LARGE	80	50
ALABAMA	SWEET POTATOES	NUTSEDGE, YELLOW	20	25
ALABAMA	SWEET POTATOES	SICKLEPOD	50	35
ARKANSAS	RICE	BARNYARDGRASS	100	50
ARKANSAS	RICE	RED RICE	60	50
ARKANSAS	RICE	SIGNALGRASS, BROADLEAF	50	30
CALIFORNIA	ALMONDS	BARNYARDGRASS	40	10
CALIFORNIA	ALMONDS	FIELD BINDWEED	15	20
CALIFORNIA	ASPARAGUS	GROUNDSEL, COMMON	70	10
CALIFORNIA	ASPARAGUS	NUTSEDGE, YELLOW	20	20
CALIFORNIA	ASPARAGUS	THISTLE, RUSSIAN	10	25
CALIFORNIA	BROCCOLI	GROUNDSEL, COMMON	50	25
CALIFORNIA	BROCCOLI	MALLOW, LITTLE	60	35
CALIFORNIA	BROCCOLI	NIGHTSHADE, HAIRY	50	40
CALIFORNIA	CARROTS	BARNYARDGRASS	70	100
CALIFORNIA	CARROTS	GROUNDSEL, COMMON	60	50
CALIFORNIA	CARROTS	PURSLANE, COMMON	25	50
CALIFORNIA	CITRUS	BARNYARDGRASS	30	5
CALIFORNIA	CITRUS	BERMUDAGRASS	15	20
CALIFORNIA	CITRUS	NUTSEDGE, YELLOW, PURPLE	15	5
CALIFORNIA	GRAPES	BARNYARDGRASS	70	10
CALIFORNIA	GRAPES	FIELD BINDWEED	15	20
CALIFORNIA	GRAPES	JOHNSONGRASS	20	30
CALIFORNIA	LETTUCE	GOOSEFOOT, NETTLELEAF	40	90
CALIFORNIA	LETTUCE	GROUNDSEL, COMMON	70	50
CALIFORNIA	LETTUCE	NETTLE, BURNING	60	50
CALIFORNIA	ONIONS	BARNYARDGRASS	50	90
CALIFORNIA	ONIONS	MALLOW, LITTLE	60	60
CALIFORNIA	ONIONS	SOWTHISTLES	60	90
CALIFORNIA	TOMATOES	BARNYARDGRASS	90	90
CALIFORNIA	TOMATOES	MALLOW, LITTLE	30	30
CALIFORNIA	TOMATOES	NIGHTSHADE, HAIRY	60	30
COLORADO	DRY BEANS	KOCHIA	50	50
COLORADO	DRY BEANS	NIGHTSHADE, HAIRY	65	30
COLORADO	DRY BEANS	PIGWEED, REDROOT	85	60
CONNECTICUT	SWEET CORN	CRABGRASS, LARGE	99	100
CONNECTICUT	SWEET CORN	LAMBSQUARTERS, COMMON	90	85
CONNECTICUT	SWEET CORN	PIGWEED, REDROOT	90	100
DELAWARE	SOYBEANS	CRABGRASS	80	85
DELAWARE	SOYBEANS	LAMBSQUARTERS	90	60
DELAWARE	SOYBEANS	MORNINGGLORIES	90	35
DELAWARE	SOYBEANS	PANICUM, FALL	70	30
FLORIDA	CUCUMBERS	AMARATH, SPINY	65	95
FLORIDA	CUCUMBERS	GOOSEGRASS	80	80
FLORIDA	CUCUMBERS	PUSLEY, FLORIDA	40	95
FLORIDA	SUGARCANE	BERMUDAGRASS	60	10
FLORIDA	SUGARCANE	ITCHGRASS	20	60
FLORIDA	SUGARCANE	PANICUM, FALL	60	50
GEORGIA	COTTON	COCKLEBUR, COMMON	80	70
GEORGIA	COTTON	MORNINGGLORIES	80	40
GEORGIA	COTTON	NUTSEDGE, YELLOW	45	30
GEORGIA	COTTON	PANICUM, TEXAS	80	40
GEORGIA	COTTON	PIGWEEDS	85	65

Table 3: Weed Species Infestations By State and Crop (Selected Species Only)

State	*Crop*	*Species*	*% Acreage Infested*	*Potential Yield Loss*
GEORGIA	COTTON	SICKLEPOD	70	40
GEORGIA	PEANUTS	BEGGARWEED, FLORIDA	80	32
GEORGIA	PEANUTS	COCKLEBUR, COMMON	35	55
GEORGIA	PEANUTS	CRABGRASS	90	40
GEORGIA	PEANUTS	MORNINGGLORY	60	28
GEORGIA	PEANUTS	NUTSEDGE, YELLOW	50	16
GEORGIA	PEANUTS	PUSLEY, FLORIDA	94	45
GEORGIA	PEANUTS	SICKLEPOD	80	35
IDAHO	HOPS	BARNYARDGRASS	100	5
IDAHO	HOPS	LAMBSQUARTERS, COMMON	100	20
IDAHO	HOPS	NIGHTSHADE	100	15
IDAHO	HOPS	PIGWEED	100	20
IDAHO	POTATOES	BINDWEED, FIELD	25	40
IDAHO	POTATOES	KOCHIA	40	25
IDAHO	POTATOES	LAMBSQUARTERS, COMMON	60	20
IDAHO	POTATOES	NIGHTSHADES	90	30
ILLINOIS	SOYBEANS	COCKLEBUR, COMMON	30	50
ILLINOIS	SOYBEANS	FOXTAILS, GIANT	95	20
ILLINOIS	SOYBEANS	JIMSONWEED	30	30
ILLINOIS	SOYBEANS	LAMBSQUARTERS, COMMON	60	60
ILLINOIS	SOYBEANS	PIGWEED, REDROOT	60	60
ILLINOIS	SOYBEANS	SMARTWEED, PENNSYLVANIA	40	30
IOWA	CORN	COCKLEBUR, COMMON	50	15
IOWA	CORN	CUPGRASS, WOOLLY	20	40
IOWA	CORN	FOXTAILS, GIANT	99	30
IOWA	CORN	PIGWEEDS	70	15
IOWA	CORN	SMARTWEED, PENNSYLVANIA	50	20
IOWA	CORN	VELVET LEAF	70	25
KANSAS	SORGHUM	COCKLEBUR, COMMON	35	70
KANSAS	SORGHUM	CRABGRASS, LARGE	80	60
KANSAS	SORGHUM	FOXTAILS	90	60
KANSAS	SORGHUM	PIGWEEDS	100	95
LOUISIANA	SUGARCANE	BERMUDAGRASS	40	15
LOUISIANA	SUGARCANE	ITCHGRASS	25	40
LOUISIANA	SUGARCANE	JOHNSONGRASS	60	50
LOUISIANA	SUGARCANE	JUNGLEGRASS	80	10
MAINE	BLUEBERRIES	BRACKENFERN	10	10
MAINE	BLUEBERRIES	BUNCHBERRY	50	20
MAINE	BLUEBERRIES	OATGRASS	50	10
MAINE	BLUEBERRIES	PANICUM, FALL	30	10
MAINE	CORN	FOXTAILS	60	50
MAINE	CORN	LAMBSQUARTERS	95	65
MAINE	CORN	NIGHTSHADES	25	50
MAINE	CORN	PIGWEEDS	95	70
MAINE	CORN	QUACKGRASS	75	80
MARYLAND	CUCUMBERS	CRABGRASS, LARGE	20	30
MARYLAND	CUCUMBERS	GOOSEGRASS	10	20
MARYLAND	CUCUMBERS	JIMSONWEED	30	30
MARYLAND	CUCUMBERS	LAMBSQUARTERS, COMMON	90	60
MARYLAND	CUCUMBERS	PIGWEED, SMOOTH	90	20
MARYLAND	CUCUMBERS	PURSLANE, COMMON	70	10
MARYLAND	WHEAT	CHICKWEED, COMMON	20	20
MARYLAND	WHEAT	GARLIC, WILD	20	10
MARYLAND	WHEAT	RYEGRASS, ITALIAN	15	15
MARYLAND	WHEAT	THISTLE, CANADA	10	10
MASSACHUSETTS	APPLES	DANDELION	90	20
MASSACHUSETTS	APPLES	ORCHARDGRASS	50	10
MASSACHUSETTS	APPLES	QUACKGRASS	25	10

Table 3: Weed Species Infestations By State and Crop (Selected Species Only)

State	*Crop*	*Species*	*% Acreage Infested*	*Potential Yield Loss*
MASSACHUSETTS	POTATOES	BARNYARDGRASS	65	35
MASSACHUSETTS	POTATOES	CRABGRASS, LARGE	95	35
MASSACHUSETTS	POTATOES	FOXTAIL, YELLOW	50	50
MASSACHUSETTS	POTATOES	LAMBSQUARTERS, COMMON	100	50
MASSACHUSETTS	POTATOES	MUSTARD, WILD	65	50
MASSACHUSETTS	POTATOES	PURSLANE, COMMON	50	35
MASSACHUSETTS	POTATOES	QUACKGRASS	35	50
MASSACHUSETTS	TOMATOES	BARNYARDGRASS	65	50
MASSACHUSETTS	TOMATOES	CRABGRASS, LARGE	95	50
MASSACHUSETTS	TOMATOES	DANDELION	40	25
MASSACHUSETTS	TOMATOES	LAMBSQUARTERS, COMMON	100	75
MASSACHUSETTS	TOMATOES	PIGWEED, REDROOT	100	75
MICHIGAN	ASPARAGUS	DANDELION	50	10
MICHIGAN	ASPARAGUS	HORSEWEED	30	30
MICHIGAN	ASPARAGUS	PANICUM, FALL	30	10
MICHIGAN	ASPARAGUS	VELVET LEAF	20	20
MICHIGAN	ONIONS	BARNYARDGRASS	80	80
MICHIGAN	ONIONS	LADYSTHUMB	60	50
MICHIGAN	ONIONS	PIGWEED, REDROOT	80	70
MICHIGAN	ONIONS	PURSLANE, COMMON	100	80
MICHIGAN	POTATOES	BARNYARDGRASS	30	30
MICHIGAN	POTATOES	CRABGRASS, LARGE	30	30
MICHIGAN	POTATOES	LAMBSQUARTERS, COMMON	50	30
MICHIGAN	POTATOES	NUT SEDGE, YELLOW	20	30
MICHIGAN	POTATOES	PIGWEED, REDROOT	60	30
MISSISSIPPI	COTTON	CRABGRASS, SOUTHERN	85	30
MISSISSIPPI	COTTON	HEMP SESBANIA	70	35
MISSISSIPPI	COTTON	JOHNSONGRASS	60	60
MISSISSIPPI	COTTON	MORNINGGLORIES	70	85
MISSISSIPPI	SOYBEANS	BARNYARDGRASS	35	40
MISSISSIPPI	SOYBEANS	COCKLEBUR, COMMON	45	55
MISSISSIPPI	SOYBEANS	JOHNSONGRASS	70	65
MISSISSIPPI	SOYBEANS	PIGWEEDS	65	60
MISSOURI	SOYBEANS	COCKLEBUR, COMMON	80	40
MISSOURI	SOYBEANS	CRABGRASS, LARGE	30	40
MISSOURI	SOYBEANS	LAMBSQUARTERS, COMMON	50	30
MISSOURI	SOYBEANS	PIGWEED, REDROOT	30	20
MONTANA	WHEAT	BROME, DOWNY	15	20
MONTANA	WHEAT	KOCHIA	40	30
MONTANA	WHEAT	OAT, WILD	60	40
MONTANA	WHEAT	THISTLE, RUSSIAN	30	20
NEW HAMPSHIRE	APPLES	CLOVER, WHITE	30	5
NEW HAMPSHIRE	APPLES	DANDELION	90	15
NEW HAMPSHIRE	APPLES	QUACKGRASS	95	35
NEW JERSEY	CUCUMBERS	GALINSOGA, HAIRY	50	100
NEW JERSEY	CUCUMBERS	NUTSEDGE, YELLOW	30	100
NEW JERSEY	CUCUMBERS	PURSLANE, COMMON	100	50
NEW JERSEY	CUCUMBERS	RAGWEED, COMMON	75	100
NEW JERSEY	TOMATOES	FOXTAILS, GIANT	50	50
NEW JERSEY	TOMATOES	LAMBSQUARTERS, COMMON	100	75
NEW JERSEY	TOMATOES	PURSLANE, COMMON	50	25
NEW JERSEY	TOMATOES	RAGWEED, COMMON	50	75
NEW MEXICO	COTTON	BARNYARDGRASS	90	15
NEW MEXICO	COTTON	CLUSTERGRASS	25	50
NEW MEXICO	COTTON	MORNINGGLORIES	60	60
NEW MEXICO	COTTON	PIGWEEDS	100	35
NEW MEXICO	HOT PEPPERS	ANODA, SPURRED	90	40
NEW MEXICO	HOT PEPPERS	BARNYARDGRASS	90	25
NEW MEXICO	HOT PEPPERS	MORNINGGLORIES	60	75
NEW MEXICO	HOT PEPPERS	PIGWEED	100	75

Table 3: Weed Species Infestations By State and Crop (Selected Species Only)

State	Crop	Species	% Acreage Infested	% Potential Yield Loss
NEW YORK	CABBAGE	CHICKWEED, COMMON	40	15
NEW YORK	CABBAGE	GALINSOGA, HAIRY	60	60
NEW YORK	CABBAGE	LAMBSQUARTERS, COMMON	100	60
NEW YORK	CABBAGE	PIGWEED, REDROOT	100	60
NEW YORK	GRAPES	CRABGRASS	100	30
NEW YORK	GRAPES	GROUNDSEL	90	10
NEW YORK	GRAPES	ORCHARDGRASS	70	50
NEW YORK	GRAPES	PIGWEED	90	50
NEW YORK	GRAPES	QUACKGRASS	70	50
NEW YORK	SWEET CORN	CRABGRASS, SMOOTH	30	25
NEW YORK	SWEET CORN	FOXTAIL, YELLOW	30	25
NEW YORK	SWEET CORN	LAMBSQUARTERS, COMMON	100	50
NEW YORK	SWEET CORN	PIGWEED, REDROOT	100	50
NORTH CAROLINA	COTTON	AMARANTH, PALMER	10	70
NORTH CAROLINA	COTTON	CRABGRASS, LARGE	85	40
NORTH CAROLINA	COTTON	LAMBSQUARTERS, COMMON	75	70
NORTH CAROLINA	COTTON	MORNINGGLORIES	85	95
NORTH CAROLINA	COTTON	PIGWEEDS	70	65
NORTH CAROLINA	COTTON	SMARTWEED, PENNSYLVANIA	20	85
NORTH CAROLINA	PEANUTS	ANODA, SPURRED	20	30
NORTH CAROLINA	PEANUTS	COCKLEBUR, COMMON	50	55
NORTH CAROLINA	PEANUTS	CRABGRASS	90	40
NORTH CAROLINA	PEANUTS	LAMBSQUARTERS, COMMON	90	35
NORTH CAROLINA	PEANUTS	NUTSEDGE, YELLOW	70	16
NORTH CAROLINA	PEANUTS	PANICUM, FALL	70	40
NORTH CAROLINA	PEANUTS	RAGWEED	75	38
NORTH DAKOTA	POTATOES	FOXTAILS	90	15
NORTH DAKOTA	POTATOES	LAMBSQUARTERS, COMMON	25	15
NORTH DAKOTA	POTATOES	MUSTARD, WILD	50	15
NORTH DAKOTA	POTATOES	PIGWEED, REDROOT	80	15
NORTH DAKOTA	SUGARBEETS	BUCKWHEAT, WILD	60	10
NORTH DAKOTA	SUGARBEETS	FOXTAILS	100	15
NORTH DAKOTA	SUGARBEETS	KOCHIA	40	25
NORTH DAKOTA	SUGARBEETS	LAMBSQUARTERS, COMMON	80	15
NORTH DAKOTA	SUGARBEETS	MUSTARD, WILD	80	20
NORTH DAKOTA	SUGARBEETS	PIGWEED, REDROOT	100	20
OKLAHOMA	COTTON	JOHNSONGRASS	40	25
OKLAHOMA	COTTON	MORNINGGLORIES	20	15
OKLAHOMA	COTTON	NIGHTSHADE, SILVERLEAF	40	15
OKLAHOMA	COTTON	PIGWEEDS	90	15
OKLAHOMA	SORGHUM	BINDWEED, FIELD	15	10
OKLAHOMA	SORGHUM	JOHNSONGRASS	30	20
OKLAHOMA	SORGHUM	KOCHIA	40	20
OKLAHOMA	SORGHUM	MORNINGGLORIES	20	15
OKLAHOMA	SORGHUM	PIGWEEDS	90	15
OREGON	MINT	AMARANTH, POWELL	80	30
OREGON	MINT	BINDWEED, FIELD	10	50
OREGON	MINT	FOXTAIL, GREEN	30	10
OREGON	MINT	GROUNDSEL, COMMON	80	5
OREGON	MINT	QUACKGRASS	10	30
OREGON	WHEAT	BINDWEED, FIELD	20	20
OREGON	WHEAT	BROME, DOWNY	70	30
OREGON	WHEAT	MUSTARD, BLUE	30	15
OREGON	WHEAT	OAT, WILD	50	10
OREGON	WHEAT	RYEGRASS, ITALIAN	30	40
OREGON	WHEAT	THIST LE, RUSSIAN	30	10
PENNSYLVANIA	CORN	FOXTAILS, GIANT	40	10
PENNSYLVANIA	CORN	LAMBSQUARTERS, COMMON	70	17

Table 3: Weed Species Infestations By State and Crop (Selected Species Only)

State	*Crop*	*Species*	*Acreage Infested*	*% Potential Yield Loss*
PENNSYLVANIA	CORN	PIGWEED, REDROOT	30	17
PENNSYLVANIA	CORN	QUACKGRASS	15	20
PENNSYLVANIA	CORN	VELVETLEAF	20	10
PENNSYLVANIA	POTATOES	BARNYARDGRASS	35	18
PENNSYLVANIA	POTATOES	BINDWEED, FIELD	20	12
PENNSYLVANIA	POTATOES	FOXTAIL, GREEN	40	18
PENNSYLVANIA	POTATOES	PANICUM, FALL	25	20
PENNSYLVANIA	POTATOES	PIGWEED, REDROOT	50	22
PENNSYLVANIA	TOMATOES	FOXTAIL, GREEN	22	12
PENNSYLVANIA	TOMATOES	LAMBSQUARTERS, COMMON	42	20
PENNSYLVANIA	TOMATOES	PIGWEED, PROSTRATE	65	15
PENNSYLVANIA	TOMATOES	SMARTWEED, PENNSYLVANIA	22	10
SOUTH DAKOTA	WHEAT	BINDWEED, FIELD	10	30
SOUTH DAKOTA	WHEAT	FOXTAIL, GREEN	85	7
SOUTH DAKOTA	WHEAT	KOCHIA	55	8
SOUTH DAKOTA	WHEAT	LAMBSQUARTERS, COMMON	40	7
SOUTH DAKOTA	WHEAT	MUSTARD, WILD	60	6
SOUTH DAKOTA	WHEAT	PIGWEED, REDROOT	35	5
TENNESSEE	COTTON	ANODA, SPURRED	15	30
TENNESSEE	COTTON	COCKLEBUR, COMMON	80	90
TENNESSEE	COTTON	CRABGRASS, LARGE	75	60
TENNESSEE	COTTON	MORNINGGLORIES	85	40
TENNESSEE	COTTON	PIGWEEDS	80	70
TENNESSEE	COTTON	VELVETLEAF	20	70
TENNESSEE	GREEN BEANS	CRABGRASS, LARGE	100	80
TENNESSEE	GREEN BEANS	FOXTAILS	75	60
TENNESSEE	GREEN BEANS	GOOSEGRASS	20	60
TENNESSEE	GREEN BEANS	PANICUM, FALL	75	60
TENNESSEE	GREEN BEANS	PIGWEEDS	80	80
TEXAS	CARROTS	AMARANTH, PALMER	40	40
TEXAS	CARROTS	CROTON, WOOLLY	30	30
TEXAS	CARROTS	JUNGLERICE	25	30
TEXAS	CARROTS	NUTSEDGE, PURPLE	40	40
TEXAS	CARROTS	ROCKET, LONDON	50	30
TEXAS	COTTON	AMARANTH, PALMER	100	70
TEXAS	COTTON	JOHNSONGRASS	75	50
TEXAS	COTTON	MORNINGGLORIES	50	75
TEXAS	COTTON	NUTSEDGE, PURPLE	20	50
TEXAS	RICE	ALLIGATORWEED	10	25
TEXAS	RICE	BARNYARDGRASS	90	50
TEXAS	RICE	JUNGLERICE	60	40
TEXAS	RICE	SIGNALGRASS, BROADLEAF	35	20
TEXAS	RICE	SPRANGLETOP, MEXICAN	25	15
VIRGINIA	GRAPES	JOHNSONGRASS	10	15
VIRGINIA	GRAPES	LAMBSQUARTERS, COMMON	30	10
VIRGINIA	GRAPES	MORNINGGLORIES	50	10
VIRGINIA	GRAPES	PIGWEED	30	10
VIRGINIA	GRAPES	RAGWEED, COMMON	50	10
VIRGINIA	PEACHES	LAMBSQUARTERS, COMMON	25	5
VIRGINIA	PEACHES	MORNINGGLORIES	40	7
VIRGINIA	PEACHES	PIGWEED	25	5
VIRGINIA	PEACHES	RAGWEED, COMMON	40	7
VIRGINIA	PEACHES	VIRGINIA CREEPER	30	15
WASHINGTON	APPLES	BINDWEED, FIELD	25	15
WASHINGTON	APPLES	FOXTAIL, YELLOW	100	5
WASHINGTON	APPLES	LAMBSQUARTERS, COMMON	100	8
WASHINGTON	APPLES	MUSTARD, TUMBLE	80	5
WASHINGTON	APPLES	PIGWEED, REDROOT	100	8
WASHINGTON	APPLES	QUACKGRASS	30	10

Table 3: Weed Species Infestations By State and Crop (Selected Species Only)

State	*Crop*	*Species*	*%* *Acreage Infested*	*Potential Yield Loss*
WASHINGTON	ASPARAGUS	BARNYARDGRASS	90	50
WASHINGTON	ASPARAGUS	BINDWEED, FIELD	15	70
WASHINGTON	ASPARAGUS	FOXTAIL, GREEN	80	30
WASHINGTON	ASPARAGUS	GROUNDSEL, COMMON	40	20
WASHINGTON	ASPARAGUS	KOCHIA	50	60
WASHINGTON	ASPARAGUS	LAMBSQUARTERS, COMMON	90	60
WASHINGTON	ASPARAGUS	PIGWEEDS	90	60
WASHINGTON	ASPARAGUS	QUACKGRASS	10	75
WASHINGTON	ASPARAGUS	THISTLE, CANADA	15	85
WASHINGT ON	GREEN PEAS	BARNYARDGRASS	20	15
WASHINGTON	GREEN PEAS	LAMBSQUARTERS, COMMON	40	30
WASHINGTON	GREEN PEAS	PIGWEED, REDROOT	30	30
WASHINGTON	GREEN PEAS	PINEAPPLE-WEED	40	25
WASHINGTON	MINT	BARNYARDGRASS	80	70
WASHINGTON	MINT	BINDWEED, FIELD	50	80
WASHINGTON	MINT	FOXTAILS	30	70
WASHINGTON	MINT	GROUNDSEL, COMMON	40	30
WASHINGTON	MINT	HORSEWEED	70	40
WASHINGTON	MINT	LAMBSQUARTERS, COMMON	90	80
WASHINGTON	MINT	LETTUCE, PRICKLY	70	50
WASHINGTON	MINT	PIGWEEDS	90	80
WASHINGTON	MINT	SALSIFIES	70	30
WASHINGTON	ONIONS	BARNYARDGRASS	90	30
WASHINGTON	ONIONS	KOCHIA	50	50
WASHINGTON	ONIONS	LAMBSQUARTERS, COMMON	90	50
WASHINGTON	ONIONS	NIGHTSHADES	90	50
WASHINGTON	ONIONS	PIGWEEDS	90	50
WASHINGTON	ONIONS	THISTLE, RUSSIAN	90	50
WASHINGTON	RASPBERRIES	BARNYARDGRASS	20	50
WASHINGTON	RASPBERRIES	CHICKWEED	100	10
WASHINGTON	RASPBERRIES	GROUNDSEL	100	20
WASHINGTON	RASPBERRIES	LAMBSQUARTERS, COMMON	100	50
WASHINGTON	RASPBERRIES	PIGWEED, REDROOT	100	50
WISCONSIN	CABBAGE	BARNYARDGRASS	15	15
WISCONSIN	CABBAGE	LAMBSQUARTERS	80	20
WISCONSIN	CABBAGE	NUTSEDGE, YELLOW	60	30
WISCONSIN	CABBAGE	PIGWEED, REDROOT	80	20
WISCONSIN	CABBAGE	QUACKGRASS	80	30
WISCONSIN	CABBAGE	VELVET LEAF	60	20
WISCONSIN	SOYBEANS	BARNYARDGRASS	100	20
WISCONSIN	SOYBEANS	CRABGRASS, LARGE	100	20
WISCONSIN	SOYBEANS	FOXTAIL, GREEN	100	20
WISCONSIN	SOYBEANS	FOXTAILS, GIANT	80	75
WISCONSIN	SOYBEANS	PANICUM, FALL	80	30
WISCONSIN	SOYBEANS	RAGWEED, COMMON	100	30
WISCONSIN	SOYBEANS	VELVETLEAF	70	40
WYOMING	DRY BEANS	BARNYARDGRASS	10	10
WYOMING	DRY BEANS	FOXTAIL, GREEN	90	20
WYOMING	DRY BEANS	KOCHIA	70	40
WYOMING	DRY BEANS	PIGWEED, REDROOT	40	25
WYOMING	DRY BEANS	THISTLE, RUSSIAN	20	10
WYOMING	WHEAT	BINDWEED, FIELD	20	30
WYOMING	WHEAT	BROME, DOWNY	35	20
WYOMING	WHEAT	BUCKWHEAT, WILD	15	10
WYOMING	WHEAT	KOCHIA	30	40
WYOMING	WHEAT	MUSTARD, TANSY	30	15

1995 Weed Survey Respondents

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Peter Fay, University of Montana	Philip Westra, Colorado State University
Robert Hartzler, Iowa State University	Leon Wrage, South Dakota State University
Robert Hayes, University of Tennessee	David Yarborough, University of Maine
Herbert Hopen, University of Wisconsin	Alan York, North Carolina State University
John Jemison, University of Maine	Bernie Zandstra, Michigan State University
James Kamas, Texas A&M University	Richard Zollinger, North Dakota State University

3.0 The NCFAP Study

A. The Forty Crops

1. Production Data

The 40 crops selected for this study are listed in Table 4 and include representative field crops, vegetable crops, fruit, nut and berry crops and specialty crops. Table 4 presents 2001 national summary production and acreage estimates for each crop. The 40 crops total 255.7 million acres, with annual production of 1.4 trillion pounds of food and fiber, and a combined value of $66.2 billion. The 40 crops account for approximately 86% of U.S. harvested acreage of all crops. (Hay crops are not included in this study). 91% of the acreage of the selected crops is accounted for by five crops (corn, cotton, sorghum, soybeans and wheat).

2. Herbicide Use

Table 5 summarizes national statistics for 2001 on herbicide use for each of the 40 crops. An estimate of the percent of the national acreage of each crop that is treated with herbicides is included. Nationally, it is estimated that 221 million acres of the 40 crops (86%) are treated with herbicides. For 30 of the 40 crops, the national acreage treated with herbicides exceeds 85%. The remaining 10 crops have considerably less acreage treated with herbicides for a variety of reasons: for wild rice (10%), only one herbicide is available; for strawberries (39%), most strawberry acreage is fumigated which provides control of weeds, insects, nematodes and diseases; for broccoli (51%), many broccoli growers use increased rates of liquid nitrogen fertilizer as foliar sprays to kill weeds; for lettuce (62%) and cucumbers (60%), these crops are often grown in fumigated soil. Several crops for which herbicide use has been traditionally low have seen herbicide-treated acreage increase in recent years as farmers adopt new production practices. (See Figure A1 [apples, more semidwarf trees], Figure A27 [wheat, more no-till acres]).

Table 5 also contains estimates of herbicide active ingredient (pounds) used annually in each crop nationally. The 40 crops total 410 million pounds in herbicide use. These national crop herbicide use totals are sums of use estimates of individual active ingredients by state and crop from NCFAP's 1997 national pesticide use database [119].

This data is available on NCFAP's website. The 1997 herbicide use estimates have been updated to 2001 for crops and states for which significant changes occurred in planted acreage or in the use of individual active ingredients since 1997 [1] [117]. The 40 crops account for approximately 90% of the volume of herbicides used in U.S. crop production. The average herbicide-treated acre receives 1.85 pounds of chemical active ingredient.

Table 5 also contains estimates of the cost of herbicides for each of the 40 crops. The cost estimate consists of three components: the cost of the product, the cost of application and technology fees for use of biotech herbicide tolerant soybean, corn, canola and cotton seeds.

Product costs are determined by multiplying estimates of the pounds of an herbicide's active ingredient by an average per-pound price for the ingredient. The average per-pound price estimates are drawn from a previous NCFAP report [120] updated to reflect recent prices [121] – [124]. Nationally it is estimated that growers of the 40 crops spent $4.7 billion on herbicide products in 2001.

Application costs are calculated by assigning an average number of herbicide application trips to each crop by state and by assigning a cost of $4/A for each application [123]. Estimates of the number of herbicide applications per treated acre are drawn from USDA surveys [152] and from USDA's Crop Profiles available at: http://ipmwww.ncsu.edu/opmppiap. Technology fees are assigned to biotech acres of corn, canola, soybeans and cotton. These technology fees are derived from a recent NCFAP report on biotechnology [280]. The costs of herbicide use including product, application and technology fees totals $6.6 billion. The average cost of herbicide treatment is $30/A.

The major acreage crops (corn, cotton, sorghum, soybeans, wheat) account for 86% of the volume of herbicide usage and 87% of the total expenditures on herbicides and their application.

Table 6 lists the herbicide use and cost data summed for the 40 crops by state. The state totals are sums of the data for each crop at the state level. The state totals shown in Table

6 do not sum to the national totals shown in Table 5 since not all crops are fully accounted for by state. Table 5 is based on national totals, which include all producing states, while Table 6 is based on a subset of states for each crop. Five states (Illinois, Indiana, Iowa, Minnesota and Nebraska) account for 41% of the volume and of the expenditures on herbicides and their application.

3. Literature Review – Weed Control

For each of the 40 crops, a literature review was conducted to collect information on current and historical usage of herbicides. This literature review is summarized for each crop in Appendices A.1-A.40. The literature review summaries include discussions of weed control practices used prior to the introduction of herbicides as well as data on weed control methods used by organic growers and experimental data comparing crop yields of herbicide-treated plots with plots treated by nonchemical means. A list of all the sources cited in Appendices A.1-A.40 is included in the reference list.

a. Historical

For most of the crops, the historical record shows the rapid adoption of herbicide use in the U.S. in the 1950s-1960s and their continued use on 80-90% of the acreage since that time (See Figure A7 [corn], Figure A8 [cotton], Figure A15 [peanuts], Figure A17 [potatoes], Figure A19 [rice], Figure A20 [soybeans], Figure A23 [sugarbeets], Figure A26 [sweet corn] and Figure A28 [wheat]). Table 7 provides an overview of the historical impacts of herbicide use for the 40 crops. For most crops, the historical literature review revealed that herbicides replaced or reduced the use of hand weeding and cultivation for weed control. Up to 120 hours of hand labor and 16 cultivation trips per acre had been used to control weeds prior to the introduction of herbicides. For some crops that are planted in dense mats (such as rice and blueberries), there was no reduction in hand weeding and cultivation since these practices were not widely used. For these crops, the impact of herbicide use was a dramatic increase in yields due to more effective weed control (rice +70%, blueberries +200%) (see Figures A2 and A18).

For most crops, there are some historical data indicating an increase in yields due to herbicide use. Most of the estimates cited in Table 7 are drawn from experiments that compared yields using herbicide treatments with yields from standard practices used historically. The period of rapid adoption of herbicide technology also was a time of other yield-enhancing changes including increased fertilization and irrigation, new plant hybrids, and the introduction of synthetic fungicides and insecticides.

Sorting out the contribution of one technological improvement is complicated. For two crops, corn and soybeans, previous studies statistically determined the contribution of herbicides to improved yields. Herbicides accounted for 20% of the increase in corn yields 1964-79 and 62% of the yield increase in soybeans 1965-79[229] [153]. For both corn and soybeans, yields increased (see Figures A6 and A21) at the same time that herbicide use increased (see Figures A7 and A20). For other crops, although no statistical studies have been conducted, there is a similar close relationship between increased crop yields and increased herbicide use (see Figures A15 – A16 [peanuts], A18 - A19 [rice], and A28 –29[wheat]). For three crops, although long-term herbicide use data are not available, it is clear from the historical record on crop yields that significant improvements in yield occurred only after the introduction of new effective herbicides (See Figures A2 [blueberries], A11 [cranberries], and A24 [sugarcane]).

For several crops, dramatic improvements in crop yield did not occur following the adoption of herbicide use (See Figures A5 [carrots], A9 [cotton], and A14 [onions]). For these crops, an adequate amount of hand labor had been previously used to remove weeds and prevent yield loss prior to the introduction of herbicides. The adoption of herbicides was spurred by a desire to reduce weed control costs since labor was becoming more expensive and scarce in the years following World War II. A mass exodus of farm labor occurred in the late 1940s and early 1950s as workers moved from rural areas to urban areas. As a result of a scarce labor supply, the farm wage rate quadrupled in the early 1950s (see Figure A30) and has increased even further since then (see Figure A31). Growers who were used to paying $.10/hour were faced with paying $.50/hour in the early 1950s and $1.00/hour in the 1960s. Herbicides were adopted to lower the costs of weeding. For example, in a 1957 experiment in onions, an $8/A herbicide application substituted for 55 hours of labor, which was budgeted at $41/A [82].

For many crops, the primary means of weed control prior to herbicides was cultivation, which can be quite effective if performed at the optimal time for weed removal. However, the historical record is clear that cultivation was not always performed in a timely fashion, particularly due to wet fields that prevented the use of tractors when weeds needed to be removed. As a result, yield losses often occurred, and in extreme cases, fields were not harvested due to weeds. In a 1932 Illinois study, it was estimated that on 10% of the cropland there was, in a normal year, one-half or greater crop loss due to weeds [314]. Cultivation lowered yields of some crops, such as potatoes and apples, due to root pruning and damage to trees. For some crops, such as corn, the need to cultivate led to very wide plant spacing to accommodate cultivation on all four sides of each plant. With the substitution of herbicides, crops such as corn could be planted closer together, which increased per acre yields.

The historical review indicated that for three crops (cranberries, carrots, and citrus) a widespread weed control tactic was the use of large quantities of oil and kerosene, which were tolerated by the crop.

The literature was searched for recent instances in which growers had no registered herbicides for effective weed control. These situations arise as a result of cancellations, the development of resistant weed populations or climate changes that lead to new weed problems. Generally, in these cases, the growers apply to EPA for an emergency registration of an effective herbicide, which is granted and adverse effects are avoided. An analysis of 66 emergency exemptions for herbicides granted by EPA in 2000 indicated that the total impact would have been $201 million in lost yields if the exemptions had not been granted [388]. Three instances were found where growers faced a weed control problem for which either no herbicide was registered, or for which available herbicides were inadequate, and no alternative or emergency registrations were forthcoming. New Jersey spinach production declined in 1989 because growers had no effective herbicide to control chickweed due to a cancellation (see Figure A22). Florida lettuce acreage declined in the 1990s due to the lack of an effective herbicide (see Figure A13). Surviving growers paid up to $700/A for hand weeders until an effective herbicide costing $20/A was registered. Sweet corn acreage in Wisconsin has declined significantly in the 1990s (see Figure A25) due to restrictions on atrazine and the lack of an effective replacement.

A recent development in the use of herbicides in U.S. crop production has been the introduction of biotech herbicide tolerant crop varieties. Four of the crops included in this Study include biotech-seeded acres, which allows the use of a herbicide that normally would kill the crop. Table 8 shows acreage estimates for these 4 biotech crops (soybean, corn, cotton and canola) by state. Following their introduction in 1995, the biotech herbicide tolerant acreage had climbed to over 70 million acres in the U.S. by 2002 (see Figure A33). Rapid expansion of canola acreage in the U.S. followed the introduction of the biotech cultivars because the herbicides made it possible to control the weeds infesting the crop (see Figure A4).

b. Organic Practices

USDA estimates that there were 1.3 million acres of organic-certified cropland in the U.S. in 2001, which represents a steady increase from 400,000 acres in 1992 [297] [305]. Figure A34 shows the recent trend in organic-certified crop acreage in the U.S. Table 9 shows estimates of certified organic crop acreage by state. California and North Dakota have more than 100,000 acres of certified organic crops. Table 10 shows estimates of certified organic crop acres for the forty crops included in this Study. No organic crop acreage estimates could be found for 15 of these crops, which suggests that there might not be any organic acres in the U.S. or that they may not have been tabulated.

Organic farmers do not use synthetic chemicals for weed, insect and disease control. The problem of controlling weeds without herbicides has been cited numerous times as the single biggest obstacle that organic growers encounter. Out of 30 research areas, organic farmers ranked weed control as the number one priority in three national surveys (1993, 1995, 1997) [296]. USDA has recently said that weed control costs of organic vegetable growers in California can be in the range of $1000/A in comparison to $50/A that conventional growers spend on herbicides [306]. The higher costs of weed control in organic production have been cited as one of the main reasons that organic products cost more for consumers [324]. Price premiums for organic soybeans and corn in 2001 were 177% and 59%, respectively [297]. Organic growers use a variety of nonchemical techniques for weed control: cover crops, rotations, flamers, vinegar, and plastic sheets for smothering weeds. These techniques provide partial control of weeds.

Organic growers rely extensively on cultivation and hand weeding during the growing season to control weeds. A literature search was conducted to identify the extent to which organic growers of the 40 crops in this Study use hand weeding and cultivation for weed control. Details are provided for each crop in Appendix A.1 through A.40 and are summarized in Table 11. For 14 of the crops, additional hand weeding of two to 165 hours per acre was required for organic production. For 14 of the crops, additional tillage of one to nine trips per acre was identified for organic production. For 6 additional crops, anecdotal information was found in the literature indicating that organic growers use hand weeding and /or tillage, although no quantification of hours or trips was made. Numerous publications and websites on organic production include photos of hand weeders [298] [312] [313]. One difficulty in assessing the costs of hand weeding for organic growers is their reliance on volunteers, interns, Mexican labor, and family (particularly children) for weeding operations [318] [298]. Some organic growers provide housing, meals and training for their workers in lieu of wages [300]. A 57-acre organic farm in California pays no wages to any of its workers [319].

Table 11 shows that for 10 of the crops, organic production yields are 13 - 80 % lower than conventional yields. Poor weed control is often cited as a major reason for lower yields in organic production [194]. University research comparing yields between conventional and organic practices indicate that yields are generally significantly higher in the conventional system. For example, a 20-year study in Iowa indicated that corn yields were 34% higher in the conventional versus the organic operations, while six to seven year studies in Nebraska and South Dakota resulted in conventional corn yields that were 17-20% higher than organic corn yields [418].

The high cost of agricultural labor in the U.S. has led to a decline in the organic acreage of certain crops in the U.S. Organic cotton acreage in the U.S. in 2001 was 25% lower than it was in 1995 [297] (See Figure A10). Buyers have determined that organic goods can be bought from other countries at a lower price because of lower production costs [326]. Thus, acreage of organic cropland is steadily increasing in countries such as Chile and India, where labor costs for hand weeding can be as low as $1/day. The organic farms in these countries are increasingly being certified as meeting organic standards by U.S.-based certification organizations [301] [302].

B. Herbicide Value Estimation

Estimates of the value of herbicides were made in terms of the economic value to growers and in terms of reduced need for labor and less soil erosion. These estimates are based on a simulation of the nonuse of herbicides by U.S. growers, the substitution of likely alternative practices, and their costs and effectiveness in comparison to herbicides.

1. Economic Value

Table 12 identifies the likely substitution of hand weeding and cultivation for each crop if herbicides were not used. These estimates are drawn from the historical record (Table 7) and from the information collected on organic practices (Table 11). For some crops, the alternatives were specified in Studies that simulated the replacement of herbicides with nonchemical practices [53]. Up to 64 hours per acre of hand weeding and up to nine cultivations have been specified as alternatives. Table 12 also specifies the cost of the alternatives. Each hour of hand weeding is estimated to cost $8.75, which includes a wage, supervisory and other costs associated with employing a work crew of hand laborers [228]. Each tillage trip is estimated to cost $4.50/A, which includes fuel, maintenance and labor charges [123]. By multiplying the per acre cost of the likely alternatives times the number of acres treated with herbicides, estimates are made of the total cost of the alternative weed control practices. These estimates are shown in Table 12. For 36 of the crops, the alternatives cost more than the use of herbicides. For the other four crops, the cost of alternatives is less because in one instance, growers are assumed not to implement any alternative practice (wild rice); for three other crops (rice, sorghum, canola), only a few cultivation trips have been specified as alternatives. The national cost of the alternatives is $14.3 billion per year, which is $7.7 billion higher than current expenditures on herbicides ($6.6 billion)

Estimates of the likely impacts on crop yields of not using herbicides and using the likely alternatives are shown in Table 13. These estimates are drawn from a series of studies conducted in the 1990s by USDA, WSSA, and AFBF [5] [17] [53] [95] [165] [182] [270]. For 35 crops, the yields are projected to decrease from 5 to 67% without herbicide use. These impact estimates are consistent with the historical record and with the record of organic production (Table 7 and Table 11). All of the studies relied on University weed science specialists to specify the likely yield changes that would result if growers used readily available alternatives to herbicides. These expert opinions are based on research trials conducted by the specialists as well their knowledge about experiences of growers who have tried alternative practices. The specialists also factored into the estimates how timely weed removal would be with cultivation and how available hand labor would be for weeding. Some of the specialists were very pessimistic regarding the availability of hand labor as a substitute for herbicides. Most specialists projected some increase in hand labor but not enough to prevent some yield loss For example, as documented in Appendix A.1-A.40, if enough hand weeding is used, yields can be equivalent to herbicides: corn (60 hours/A), cotton (67 hours/A), lettuce (224-424 hours/A), onions (1067 hours/A), and tomatoes (182-259 hours/A). These labor requirements are far greater than those specified as likely affordable alternatives: corn (5 hours), cotton (13 hours), lettuce (38 hours), onions (64 hours), and tomatoes (37 hours).

For four crops, no yield change is projected since the amount of tillage, hand weeding or other alternative practice is assumed sufficient to provide control equivalent to herbicides (celery, citrus, hot peppers and raspberries). In addition, for grapes, the national loss is 1%, which is a weighted average of no loss in California and a 12-35% loss in other states.

This method of relying on University experts to interpret scientific data and take into account economic and weather factors to project potential statewide yield changes has been used in national pesticide benefit assessments for thirty years. This method is relied on by the EPA when it makes decisions regarding emergency herbicide use registrations. In these cases, the University specialists make estimates of statewide yield losses likely to result if EPA does not grant the registration.

In total, as shown in Table 13, the nonuse of herbicides and the likely substitution of alternatives would result in a loss of $13.3 billion in food and fiber production due to less effective weed control. The total loss in production would amount to 288 billion pounds, which represents approximately 21% of the national production of the 40 crops.

Table 14 summarizes the economic impacts of the nonuse of herbicides for the 40 crops included in this Study. The total impact is a loss of $21 billion, which includes $7.7 billion in increased costs for weed control and $13.3 billion in yield losses due to less effective weed control. Four crops (corn, cotton, soybeans and wheat) account for 71% of the total loss. Table 14 also includes an estimated Net Return Ratio (NRR), which is the ratio of the total impact estimate to the estimate of current expenditures on herbicides. For the nation, the Net Return Ratio is 3.20, which means that for every dollar currently spent on herbicides the grower gains $3.20. There are three crops for which the net return ratio is greater than 50: carrots (75), wild rice (54) and strawberries (91).

Table 15 summarizes the economic impact estimates by state. Table 16 includes a selected list of crop impacts for each state. Table 17 summarizes the production volume loss by state.

2. Labor Requirements

One of the major replacements for herbicides identified in this Study is increased use of hand labor for weeding. Field crops such as wheat, corn and soybeans are projected at 2-5 additional hours of hand weeding per acre. Most fruit and vegetable crops are projected at 20-60 hours per acre. The additional cost of hand weeding is included in the impact estimates by crop in Table 12 and by state in Table 15. In addition, the number of additional workers that would be required to implement the increased hand weeding is estimated. Table 18 presents estimates of the total number of additional hours of hand labor that would be required by crop. For the nation, an additional 1.2 billion hours of hand weeding would be required. These estimates are also shown in terms of the number of workers that would be required by assuming that for each crop the weeding would need to be done during a 4-week period. For the nation, an additional 7.2 million laborers would be required. Table 19 presents the labor requirement estimates by state. It should be noted that U.S. farms currently employ approximately one million workers per year, which is a substantial reduction from earlier times (see Figure A32).

As noted above, the hand weeding requirements specified in this Study are not sufficient to prevent yield losses. For major acreage crops such as corn, approximately 10% of the labor necessary to prevent yield loss is actually specified as a replacement (5 hours vs. 60 hours). An approximate estimate of the amount of labor that would be required to prevent any yield loss in comparison to herbicides is ten times that specified in this Study, or an additional 72 million workers at the peak time for hand weeding.

3. Soil Erosion

Erosion of cropland has been reduced in the U.S. from an estimated 3.5 billion tons in 1938 to 1.0 billion tons in 1997 [342] [343]. Sheet and rill erosion has been reduced by soil conserving tillage and other conservation practices. The tillage reduction, which resulted from the increased use of herbicides for weed control, played a significant role in erosion reduction in the U.S. Herbicides replaced tillage for weed control. Acceptance of conservation tillage by farmers has depended upon the availability of herbicides that provide suitable weed control [344]. No-till, in which the soil is left undisturbed by tillage and the residue is left on the soil surface, is the most effective soil-conserving system [345]. No-till systems can reduce erosion by 90% or more. As tillage is reduced, reliance on herbicides increases [346]. The elimination of tillage means that the grower must rely entirely on herbicides to control weeds [347] [348]. No-till acreage has increased steadily in the past decade (See Figure A35). Currently, there are 52 million acres of no-till cropland in the U.S. The average rate of erosion on a cultivated crop acre is 2.9 tons greater than the rate on an uncultivated acre. Table 20 shows estimates of no-till acreage and estimates of the difference in erosion rates between cultivated and non-cultivated acres by state. The adoption of no-till practices prevents annual erosion of 304 billion pounds.

This Study projects a significant increase in cultivation for weed control if herbicides were not used in crop production. Much of this increase is row cultivation during the growing season. It is not possible to quantify the impacts on soil erosion amounts as a result of an increase in row cultivation. The scientific literature indicates that row cultivation can reduce runoff from cropland as a result of breaking the soil crust and improving water infiltration [349] [350]. The research has shown that soil loss is not significantly affected by row cultivation [351].

On the other hand, without herbicides, U.S. farmers could no longer grow crops using no-till methods. Without herbicides, farmers who currently use no-till methods would have to use tillage not only down the row during the growing season but also for removing weeds prior to planting. As a result, the acres that are currently in no-till would no longer be subject to the lower erosion rates associated with non-cultivated cropland but, rather, would be likely to erode at the higher rates associated with cultivated acres (see Table 20). This Study projects the national impact on erosion to be an increase of 304 billion pounds/year as a result of growers no longer using no-till methods, which would occur if herbicides were not used. Table 20 shows these erosion estimates by state.

Table 4: U.S. Production: 40 Crops, 2001			
		Production	
Crop	***Acreage (000)***	***Value (million $)***	***Volume (million lbs)***
ALMONDS	525	732	1,354
APPLES	430	1,477	9,628
ARTICHOKES	8	58	100
ASPARAGUS	77	230	208
BLUEBERRIES	24	23	75
BROCCOLI	141	504	2,042
CANOLA	1,494	176	1,998
CARROTS	121	577	4,005
CELERY	29	277	1,882
CITRUS	1,094	2,638	34,806
CORN	75,752	19,209	736,000
COTTON	15,787	3,384	9,600
CRANBERRIES	34	99	532
CUCUMBERS	59	212	1,089
DRY BEANS	1,430	414	1,954
GRAPES	930	2,921	13,104
GREEN BEANS	210	112	1,397
GREEN PEAS	217	102	774
HOPS	36	126	66
HOT PEPPERS	33	88	311
LETTUCE	306	1,907	10,053
MINT	98	96	8
ONIONS	167	703	6,708
PEACHES	151	496	2,440
PEANUTS	1,543	1,003	4,239
POTATOES	1,267	2,591	44,476
RASPBERRIES	12	46	92
RICE	3,335	896	21,304
SORGHUM	10,252	998	28,784
SOYBEANS	74,105	12,446	174,000
SPINACH	15	17	284
STRAWBERRIES	47	1,085	1,666
SUGARBEETS	1,371	1,113	52,000
SUGARCANE	1,029	942	70,000
SUNFLOWERS	2,653	317	3,480
SWEET CORN	733	772	9,050
SWEET POTATOES	98	210	1,435
TOMATOES	411	1,665	22,192
WHEAT	59,617	5,553	120,000
WILD RICE	19	10	6
TOTAL	255,660	66,225	1,393,136

Source: [1], [2], [13], [15], [118]

Notes: Corn for grain only, spinach, green beans, and green peas for processing only. Wild Rice - Minnesota only; Blueberries – Maine only.

Table 5: Herbicide Use and Cost by Crop, 2001						
Crop	***Acres Treated (000)***		***Lbs./Year (000)***[1]	***Cost $/Year (000)***[1]		
	%[2]	***(000)***		***Total***	***Product***	***Application and Tech Fees***
ALMONDS	86	452	1,229	20,533	16,921	3,612
APPLES	63	271	1,530	17,715	16,610	1,105
ARTICHOKES	58	5	12	419	401	18
ASPARAGUS	91	70	213	2,833	2,282	551
BLUEBERRIES	95	23	14	652	472	180
BROCCOLI	51	70	211	2,398	2,109	289
CANOLA	99	1,479	718	30,603	13,278	17,325
CARROTS	98	119	169	3,739	2,871	868
CELERY	85	25	50	696	511	185
CITRUS	95	1,039	7,879	80,607	72,365	8,242
CORN	98	74,237	206,052	2,265,353	1,823,501	441,852
COTTON	95	14,998	33,113	559,963	344,195	215,768
CRANBERRIES	95	32	120	3,109	2,850	259
CUCUMBERS	60	35	252	3,505	2,701	804
DRY BEANS	99	1416	3,799	40,030	34,775	5,255
GRAPES	75	698	1,831	27,932	24,691	3,241
GREEN BEANS	96	202	743	6,548	5,108	1,440
GREEN PEAS	94	204	245	4,051	3,366	685
HOPS	95	34	71	1,201	1,065	136
HOT PEPPERS	95	31	111	1,547	1,475	72
LETTUCE	62	190	290	8,477	7,955	522
MINT	95	93	375	10,392	9,648	744
ONIONS	88	147	568	8,268	7,149	1,119
PEACHES	66	100	234	2,978	2,563	415
PEANUTS	97	1,497	3,038	63,896	48,250	15,646
POTATOES	93	1,178	3,109	45,450	38,505	6,945
RASPBERRIES	91	11	34	674	618	56
RICE	98	3,268	15,736	217,996	179,170	38,826
SORGHUM	91	9,329	16,579	134,918	103,731	31,187
SOYBEANS	96	71,141	76,604	2,110,780	1,224,075	886,705
SPINACH	90	14	37	471	414	57
STRAWBERRIES	39	18	75	1,420	1,210	210
SUGARBEETS	98	1,344	2,398	138,163	118,434	19,729
SUGARCANE	95	977	5,904	51,323	43,678	7,645
SUNFLOWERS	95	2,520	1,841	26,347	18,408	7,939
SWEET CORN	90	660	1,890	16,134	13,700	2,434
SWEET POTATOES	70	69	71	1,664	1,390	274
TOMATOES	96	394	684	11,593	8,517	3,076
WHEAT	55	32,789	21,789	649,779	503,606	146,173
WILD RICE	10	2	1	9	1	8
TOTAL[3]	(86)	221,181	409,619	6,574,166	4,702,569	1,871,597

[1] See Text for calculation methodology.

[2] These estimates are from USDA surveys and assessments [14], [16], [17], [117], [182], [270]. For crops not included in the surveys, see Appendices A.1 - A.40. Fumigants not included.

[3] National per acre values: lbs/A (1.85); cost/A ($29.72)

Table 6: Herbicide Use and Cost By State, 2001				
State	***Lbs (000/yr)***	***Application and Tech Fees (000$/yr)***	***Product Cost (000$/yr)***	***Total Cost (000$/yr)***
ALABAMA	2,866	15,824	29,310	45,134
ARIZONA	1,087	6,552	13,899	20,421
ARKANSAS	13,812	74,160	150,187	224,347
CALIFORNIA	12,606	34,167	166,999	201,166
COLORADO	2,690	14,839	32,911	47,750
CONNECTICUT	124	23	987	1,010
DELAWARE	964	3,594	12,925	16,519
FLORIDA	9,281	13,756	82,774	96,530
GEORGIA	6,056	35,767	69,115	104,882
IDAHO	3,246	12,292	73,184	85,476
ILLINOIS	44,262	192,229	460,051	652,280
INDIANA	23,768	103,780	235,261	339,041
IOWA	51,094	208,424	600,270	808,694
KANSAS	18,411	80,868	151,625	232,493
KENTUCKY	5,263	21,819	69,084	90,903
LOUISIANA	12,169	36,249	121,741	157,990
MAINE	189	466	3,478	3,944
MARYLAND	2,365	9,201	29,048	38,249
MASSACHUSETTS	169	144	2,386	2,530
MICHIGAN	10,352	41,891	96,107	137,998
MINNESOTA	22,596	151,380	373,858	525,238
MISSISSIPPI	9,343	49,931	111,669	161,600
MISSOURI	16,269	81,614	190,929	272,543
MONTANA	2,983	16,397	38,148	54,545
NEBRASKA	28,922	110,914	272,656	383,570
NEVADA	9	43	136	179
NEW HAMPSHIRE	49	13	384	397
NEW JERSEY	674	1,961	11,984	13,945
NEW MEXICO	855	2,398	7,387	9,785
NEW YORK	4,688	6,168	35,808	41,976
NORTH CAROLINA	6,311	38,004	65,893	103,897
NORTH DAKOTA	13,774	99,949	263,958	363,907
OHIO	14,973	74,478	152,534	227,012
OKLAHOMA	2,601	18,494	31,514	50,008
OREGON	1,503	6,327	23,370	29,697
PENNSYLVANIA	5,434	12,564	43,120	55,684
RHODE ISLAND	10	3	69	72
SOUTH CAROLINA	2,888	12,525	32,547	45,072
SOUTH DAKOTA	14,645	91,632	200,347	291,979
TENNESSEE	4,383	29,775	54,606	84,381
TEXAS	18,509	97,984	171,979	269,963
UTAH	183	599	1,507	2,106
VERMONT	339	11	2,337	2,348
VIRGINIA	2,803	10,471	31,307	41,778
WASHINGTON	4,393	13,824	65,690	79,514
WEST VIRGINIA	268	261	2,041	2,302
WISCONSIN	9,161	37,190	109,403	146,593
WYOMING	268	1,229	6,043	7,272

Note: Includes the 40 crops identified in Table 5 summed by state.

Table 7: Historical Summary, Herbicide Impacts	
Crop	
ALMONDS	Replaced 16 cultivations/A, replaced 7 hours hand labor/A [197]
APPLES	Replaced cultivations and 2-3 hand hoeings [333]
ARTICHOKES	Reduced tillage
ASPARAGUS	Replaced 4-6 cultivations/A [205]
BLUEBERRIES	Yield up 200% [212], [213]
BROCCOLI	Replaced 20 hours/A hand weeding; yields up 30% [249], [320]
CANOLA	Expanded acreage and production by 75% [202]
CARROTS	Replaced 28 hours/A hand weeding; replaced 50 gallons oil/A [193], [19]
CELERY	Replaced 30-60 hours hand weeding/A [340]
CITRUS	Replaced 90 gal oil/A (CA) replaced 8 cultivations, 2-3 hand weedings/A (FL) [41], [47], [52]
CORN	Replaced hand weeding; replaced 4 cultivations/A; yield improved 15-25% [316]
COTTON	Replaced 20-40 hrs hand weeding; replaced 5-7 cultivations [160], [162]
CRANBERRIES	Replaced 300 gallons kerosene/A [30]; yields up 150% [35], [38]
CUCUMBERS	Replaced cultivation; yields 24% higher [246]
DRY BEANS	Replaced hoeing of 16 hours/A; yields 38% higher [4]
GRAPES	Replaced cultivation (CA); replaced cultivation and hoeing (NY) [59], [64]
GREEN BEANS	Replaced hand weeding and cultivation [291]
GREEN PEAS	Replaced hand labor [283]
HOPS	Replaced 20-50 hours of hand labor [416]
HOT PEPPERS	Reduced hand hoeing
LETTUCE	Reduced hoeing time 55% [18]
MINT	Replaced 18 hours of hand weeding [411]
ONIONS	Reduced hoeing time by 120 hours/A [82]
PEACHES	Replaced 7 tillage trips [235]
PEANUTS	Replaced 5 tillage trips; replaced 14 hours hand weeding [89], [354]
POTATOES	Replaced 6 tillage trips [108]
RASPBERRIES	Replaced 9 tillage trips and 43 hours hand weeding [23], [24]
RICE	Yield up 70% [133]
SORGHUM	Replaced 3 cultivations; yields up 34% [70]
SOYBEANS	Replaced 4 cultivations; yields up 10% [145], [146]
SPINACH	Replaced hand weeding and cultivations [287]
STRAWBERRIES	Replaced 16-40 hours hand weeding [262]
SUGARBEETS	Replaced 31 hours hand weeding and thinning [186]
SUGARCANE	Replaced 40-70 hours hand weeding [102]; replaced 3 cultivations [105]
SUNFLOWERS	Significant production began in 1970's; no history prior to herbicides
SWEET CORN	Reduced cultivations
SWEET POTATOES	Replaced hand weeding 24-30 hours/A [10], [11]
TOMATOES	Replaced 3-6 cultivations; 9-16 hours hand labor [174], [175]
WHEAT	Replaced hand weeding; reduced cultivation; improved yields [393]
WILD RICE	Significant production began in the 1960's; herbicide use minimal

See Appendices A.1-A.40 for details.

Table 8: Biotech Herbicide Tolerant Crop Acreage by State, 2001					
	Thousand Acres				
State	***Soybeans***	***Cotton***	***Corn***	***Canola***	***Total***
ALABAMA	112	354			466
ARIZONA		78	7		85
ARKANSAS	1920	614	24		2558
CALIFORNIA		276	30		306
COLORADO			130		130
CONNECTICUT			3		3
DELAWARE	170		19		189
FLORIDA	12	108			120
GEORGIA	128	1005			1133
IDAHO			9		9
ILLINOIS	6688		331		7019
INDIANA	4391		333		4724
IOWA	7796		960		8756
KANSAS	2000		384		2384
KENTUCKY	472		25		497
LOUISIANA	661	404			1065
MAINE			2		2
MARYLAND	335		40		375
MASSACHUSETTS			4		4
MICHIGAN	1227		158		1385
MINNESOTA	4504		726	63	5293
MISSISSIPPI	995	832			1827
MISSOURI	3450	248	277		3975
MONTANA					-
NEBRASKA	3477		564		4041
NEVADA					-
NEW HAMPSHIRE					-
NEW JERSEY	69		4		73
NEW MEXICO			72		72
NEW YORK	112				112
NORTH CAROLINA	1006	725	46		1777
NORTH DAKOTA	906		186	871	1963
OHIO	2842		132		2974
OKLAHOMA	186	198	8		392
OREGON					-
PENNSYLVANIA	316		130		446
RHODE ISLAND					-
SOUTH CAROLINA	352	228			580
SOUTH DAKOTA	3496		654		4150
TENNESSEE	978	502	71		1551
TEXAS	169	3657	266		4092
UTAH			7		7
VERMONT			4		4
VIRGINIA	318	72	33		423
WASHINGTON					-
WEST VIRGINIA	14				14
WISCONSIN	914		165		1079
WYOMING			3		3
TOTAL	50016	9301	5807	934	66058

Source: [280]

Table 9: Organic Crop Acreage By State	
State	***Acres***
ALABAMA	35
ARIZONA	8,820
ARKANSAS	24,769
CALIFORNIA	148,664
COLORADO	67,347
CONNECTICUT	1,107
DELAWARE	-
FLORIDA	12,059
GEORGIA	489
IDAHO	64,982
ILLINOIS	20,459
INDIANA	3,996
IOWA	71,796
KANSAS	24,299
KENTUCKY	5,272
LOUISIANA	86
MAINE	7,756
MARYLAND	3,095
MASSACHUSETTS	1,169
MICHIGAN	45,466
MINNESOTA	98,256
MISSISSIPPI	-
MISSOURI	11,973
MONTA NA	71,707
NEBRASKA	43,960
NEVADA	1,856
NEW HAMPSHIRE	485
NEW JERSEY	6,795
NEW MEXICO	8,848
NEW YORK	42,099
NORTH CAROLINA	1,372
NORTH DAKOTA	144,890
OHIO	36,868
OKLAHOMA	3,530
OREGON	22,075
PENNSYLVANIA	16,272
RHODE ISLAND	163
SOUTH CAROLINA	14
SOUTH DAKOTA	49,984
TENNESSEE	300
TEXAS	45,219
UTAH	30,086
VERMONT	24,235
VIRGINIA	4,352
WASHINGTON	31,229
WEST VIRGINIA	358
WISCONSIN	79,128
WYOMING	16,196
TOTAL	1,303,916

Source: [98]
Note: Certified Acres Only

Table 10: Organic Acreage by Crop		
Crop	***Acres***	***% of U.S. Acreage***
ALMONDS	10,000	2
APPLES	12,189	3
ARTICHOKES[1]	240	3
ASPARAGUS[1]	428	1
BLUEBERRIES	NI	-
BROCCOLI[1]	2333	2
CANOLA	NI	-
CARROTS	4,757	4
CELERY[1]	591	2
CITRUS	9,741	1
CORN	93,551	<1
COTTON	11,456	<1
CRANBERRIES	NI	-
CUCUMBERS[1]	228	<1
DRY BEANS	15,080	1
GRAPES	14,532	2
GREEN BEANS	NI	-
GREEN PEAS	NI	-
HOPS	NI	-
HOT PEPPERS	NI	-
LETTUCE	16,073	5
MINT	NI	-
ONIONS[1]	782	<1
PEACHES[1]	688	<1
PEANUTS	4,653	<1
POTATOES	7,533	1
RASPBERRIES	NI	-
RICE	29,022	1
SORGHUM	938	<1
SOYBEANS	174,467	<1
SPINACH[1]	NI	-
STRAWBERRIES[1]	1279	3
SUGARBEETS	NI	-
SUGARCANE	NI	-
SUNFLOWERS	15,295	1
SWEET CORN	NI	-
SWEET POTATOES	NI	-
TOMATOES	3,451	1
WHEAT	194,640	<1
WILD RICE	NI	-

Data for 2001 [98] [321] [311]
NI: No Information

[1] California only [389] [352]

Table 11: Organic Weed Control Practices/Crop Yields	
Crop	
ALMONDS	Cover crops and irrigation, 7 hours hoeing/A [199]
APPLES	Hand hoeing (20 hrs/A) plus two diskings [338]
ARTICHOKES	NI
ASPARAGUS	Weeds are the most serious problem [209]
BLUEBERRIES	Yields 75% lower [215]
BROCCOLI	22 hours hand weeding/A; 4 cultivations/A [299]
CANOLA	NI
CARROTS	Hand weeding/cultivation; weeds are biggest cost [22]
CELERY	NI
CITRUS	Cultivation (5 times) hand weeding (4 times) (FL) [55]
CORN	13-25% reduction in yield [361] [260]
COTTON	9 cultivations; 12 hours hand weeding; yields 50% lower [323] [324]
CRANBERRIES	NI
CUCUMBERS	30 hours hand weeding; 3 cultivations [84]
DRY BEANS	NI
GRAPES	8 hrs hand weed & 1 cult.(CA); 8 cult. & 13 hrs hand weed, yld: –35% (NY) [60], [62]
GREEN BEANS	17 hours hand weeding; 6 cultivations [299]
GREEN PEAS	12 hours hand weeding [285]
HOPS	NI
HOT PEPPERS	NI
LETTUCE	2 cultivations; 18 hours hand weeding [84]
MINT	NI
ONIONS	6 cultivations; 73 hours hoeing [84]
PEACHES	NI
PEANUTS	50-165 hours, 2 cultivations [94]
POTATOES	Yields 25-36% lower [303], [308]
RASPBERRIES	Hand weeding and cultivation [28]
RICE	Yields 50% lower [138]; 3 cultivations before planting [387]
SORGHUM	NI
SOYBEANS	6 tillage trips; 5 hours hand weeding/A [304], [310]
SPINACH	NI
STRAWBERRIES	Hand weeding; yields 40-75% lower [264], [265]
SUGARBEETS	NI
SUGARCANE	NI
SUNFLOWERS	Yields 25% lower [260]
SWEET CORN	3-5 cultivations [84]; 2 hours hand labor [299]
SWEET POTATOES	NI
TOMATOES	6 cultivations; 15 hours hand weeding [181]; yields 17% lower [194]
WHEAT	Yields are 25-80% lower [260] [309]
WILD RICE	NI

NI: No Information; See Appendices A.1-A.40 for details.

Table 12: No Herbicide Use, Alternative Costs by Crop					
				Cost	
Crop	*Hand Weeding (Hrs/A)*[1]	*Tillage (Trips/A)*[1]	*Other ($/A)*	*($/A)*[2]	*(000 $/year)*[3]
ALMONDS	7	0	36[4]	97.25	43,957
APPLES	20	2		184.00	49,864
ARTICHOKES	23	0		201.25	1,006
ASPARAGUS	5	5		66.25	4,638
BLUEBERRIES	5	0		43.75	1,006
BROCCOLI	20	2		184.00	12,880
CANOLA	0	2		9.00	13,311
CARROTS	14	2		131.50	15,648
CELERY	60	4		543.00	13,575
CITRUS	0	0	400[5]	400.00	415,600
CORN	5	4		61.75	4,584,134
COTTON	13	7		145.25	2,178,459
CRANBERRIES	20	0		175.00	5,600
CUCUMBERS	30	3		276.00	9,660
DRY BEANS	16	2		149.00	210,984
GRAPES	8	2		79.00	55,142
GREEN BEANS	12	2		114.00	23,028
GREEN PEAS	12	2		114.00	23,256
HOPS	35	6		333.25	11,330
HOT PEPPERS	60	0		525.00	16,275
LETTUCE	38	2		341.50	64,885
MINT	18	0		157.50	14,647
ONIONS	64	2		569.00	83,643
PEACHES	6	0		52.50	5,250
PEANUTS	10	2		96.50	144,460
POTATOES	10	5		110.00	129,580
RASPBERRIES	43	9		416.75	4,584
RICE	0	4		18.00	58,824
SORGHUM	0	3		13.50	125,941
SOYBEANS	5	4		61.75	4,392,956
SPINACH	20	3		188.50	2,639
STRAWBERRIES	30	4		280.50	5,049
SUGA RBEETS	15	2		140.25	188,496
SUGARCANE	25	3		232.25	226,908
SUNFLOWERS	0	7		31.50	79,380
SWEET CORN	5	3		57.25	37,785
SWEET POTATOES	24	2		219.00	15,111
TOMATOES	37	8		359.75	141,741
WHEAT	2	2		26.50	868,908
WILD RICE	0	0		0	0
TOTAL				(64.56)	14,280,140

[1] Weighted national averages, see Appendices A.1 – A.40.
[2] Hand weeding costs calculated at $8.75/hour [228], cultivation costs calculated at $4.50/trip [123].
[3] Cost per acre times number of acres treated with herbicides (Table 5)
[4] Mowing, cover crops (see Appendix A.1)
[5] Mowing, increased fertilizer and irrigation (see Appendix A.10)

Table 13: No Herbicide Use, Production Impacts By Crop			
		Production [1]	
Crop	***% Yield Loss w/o Herbicides*** [2]	***Million Lbs***	***Million $***
ALMONDS	5	58.2	31.5
APPLES	15	909.8	139.6
ARTICHOKES	16	9.3	5.4
ASPARAGUS	55	104.1	115.1
BLUEBERRIES	67	47.7	14.6
BROCCOLI	14	145.8	36.0
CANOLA	45	890.1	78.4
CARROTS	48	1,884.0	271.4
CELERY	0	0	0
CITRUS	0	0	0
CORN	20	144,256.0	3,765.0
COTTON	27	2,462.4	868.0
CRANBERRIES	50	252.7	47.0
CUCUMBERS	66	431.2	84.0
DRY BEANS	25	483.6	102.5
GRAPES	1	98.3	21.9
GREEN BEANS	20	268.2	21.5
GREEN PEAS	20	145.5	19.2
HOPS	25	15.7	29.9
HOT PEPPERS	0	0	0
LETTUCE	13	810.3	153.7
MINT	58	4.4	53.0
ONIONS	43	2,538.3	266.0
PEACHES	11	177.1	36.0
PEANUTS	52	2,138.2	505.9
POTATOES	32	13,236.1	771.1
RASPBERRIES	0	0	0
RICE	53	11,065.3	465.4
SORGHUM	26	6,810.3	236.1
SOYBEANS	26	43,430.4	3,106.5
SPINACH	50	127.8	7.6
STRAWBERRIES	30	194.9	126.9
SUGARBEETS	29	14,778.4	316.3
SUGARCANE	25	16,625.0	223.7
SUNFLOWERS	16	529.0	48.2
SWEET CORN	25	2,036.2	173.7
SWEET POTATOES	20	200.9	29.4
TOMATOES	23	4,900.0	367.6
WHEAT	25	16,500.0	763.0
WILD RICE	50	0.3	0.5
TOTAL	(21)	288,565.5	13,301.6

[1] Calculated with % yield loss estimates (column 1), production estimates in Table 4, and % acres treated (Table 5).

[2] See Appendices A.1 - A.40 for sources. Primary sources include [5], [17], [53], [95], [165], [182] and [270]. Percent lost on current herbicide-treated acres if herbicides not used.

Table 14: Summary of No Herbicide Use Impacts by Crop (000 $)						
Crop	Weed Control Cost			Production Impact (-)[1]	Total Impact[2] (-)	NRR [3]
	Current Herbicide[4]	Alternative[5]	Net (+)			
ALMONDS	20,533	43,957	23,424	31,500	54,924	2.67
APPLES	17,715	49,864	32,149	139,600	171,749	9.70
ARTICHOKES	419	1,006	587	5,400	5,987	14.29
ASPARAGUS	2,833	4,638	1,805	115,100	116,905	41.26
BLUEBERRIES	652	1,006	354	14,600	14,954	22.93
BROCCOLI	2,398	12,880	10,482	36,000	46,482	19.38
CANOLA	30,603	13,311	-17,292	78,400	61,108	2.00
CARROTS	3,739	15,648	11,909	271,400	283,309	75.77
CELERY	696	13,575	12,879	0	12,879	18.50
CITRUS	80,607	415,600	334,993	0	334,993	4.16
CORN	2,265,353	4,584,134	2,318,781	3,765,000	6,083,781	2.69
COTTON	559,963	2,178,459	1,618,496	868,000	2,486,496	4.44
CRANBERRIES	3,109	5,600	2,491	47,000	49,491	15.92
CUCUMBERS	3,505	9,660	6,155	84,000	90,155	25.72
DRY BEANS	40,030	210,984	170,954	102,500	273,454	6.83
GRAPES	27,932	55,142	27,210	21,900	49,110	1.76
GREEN BEANS	6,548	23,028	16,480	21,500	37,980	5.80
GREEN PEAS	4,051	23,256	19,205	19,200	38,405	9.48
HOPS	1,201	11,300	10,129	29,900	40,029	33.33
HOT PEPPERS	1,547	16,275	14,728	0	14,728	9.52
LETTUCE	8,477	64,885	56,408	153,700	210,108	24.79
MINT	10,392	14,647	4,255	53,000	57,255	5.51
ONIONS	8,268	83,643	75,375	266,000	341,375	41.29
PEACHES	2,978	5,250	2,272	36,000	38,272	12.85
PEANUTS	63,896	144,460	80,564	505,900	586,464	9.18
POTATOES	45,450	129,580	84,130	771,100	855,230	18.82
RASPBERRIES	674	4,584	3,910	0	3,910	5.80
RICE	217,996	58,824	-159,172	465,400	306,228	1.40
SORGHUM	134,918	125,941	-8,977	236,100	227,123	1.68
SOYBEANS	2,110,780	4,392,956	2,282,176	3,106,500	5,388,676	2.55
SPINACH	471	2,639	2,168	7,600	9,768	20.74
STRAWBERRIES	1,420	5,049	3,629	126,900	130,529	91.92
SUGARBEETS	138,163	188,496	50,333	316,300	366,633	2.65
SUGARCANE	51,323	226,908	175,585	223,700	399,285	7.78
SUNFLOWERS	26,347	79,380	53,033	48,200	101,233	3.84
SWEET CORN	16,134	37,785	21,651	173,700	195,351	12.11
SWEET POTATOES	1,664	15,111	13,447	29,400	42,847	25.75
TOMATOES	11,593	141,741	130,148	367,600	497,748	42.94
WHEAT	649,779	868,908	219,129	763,000	982,129	1.51
WILD RICE	9	0	-9	500	491	54.55
TOTAL	6,574,166	14,280,140	7,705,974	13,301,600	21,007,574	3.20

[1] From Table 13
[2] In calculating total impact, an increase in net cost is considered a loss.
[3] NRR: Net Return Ratio; the ratio of the total impact to current herbicide costs.
[4] From Table 5
[5] From Table 12

Table 15: Summary of No Herbicide Use Impacts by State (000$)					
State	***Production Impact***	***Weed Control Cost***			***Total Impact***
		Current Herbicide	***Alternative***	***Net***	
ALABAMA	164,275	45,134	124,687	79,553	243,828
ARIZONA	84,058	20,333	67,972	47,639	131,697
ARKANSAS	671,917	224,274	368,962	144,688	816,605
CALIFORNIA	899,173	201,034	560,247	359,213	1,258,386
COLORADO	109,045	47,324	138,291	90,967	200,012
CONNECTICUT	1,259	150	513	363	1,622
DELAWARE	36,195	16,162	21,012	4,850	41,045
FLORIDA	485,132	96,165	452,225	356,060	841,192
GEORGIA	532,769	104,882	300,628	195,746	728,515
IDAHO	402,178	85,089	127,801	42,712	444,890
ILLINOIS	1,191,742	652,061	1,303,069	651,008	1,842,750
INDIANA	446,818	339,007	695,882	356,875	803,693
IOWA	1,434,355	808,445	1,342,601	534,156	1,968,511
KANSAS	221,626	232,452	489,958	257,506	479,132
KENTUCKY	102,390	90,866	136,151	45,285	147,675
LOUISIANA	353,432	157,984	304,423	146,439	499,871
MAINE	35,206	3,364	8,251	4,887	40,093
MARYLAND	62,392	38,016	59,766	21,750	84,142
MASSACHUSETTS	18,654	1,829	3,302	1,473	20,127
MICHIGAN	436,220	137,923	343,486	205,563	641,783
MINNESOTA	488,454	524,251	973,653	449,402	937,856
MISSISSIPPI	335,522	161,583	335,706	174,123	509,645
MISSOURI	632,296	272,365	516,680	244,315	876,611
MONTANA	95,622	54,259	111,658	57,399	153,021
NEBRASKA	444,856	383,206	831,663	448,457	893,313
NEVADA	4,229	120	767	647	4,876
NEW HAMPSHIRE	759	48	405	357	1,116
NEW JERSEY	67,381	13,882	15,170	1,288	68,669
NEW MEXICO	27,779	9,747	38,208	28,461	56,240
NEW YORK	106,223	40,325	67,831	27,506	133,729
NORTH CAROLINA	348,218	103,847	288,803	184,956	533,174
NORTH DAKOTA	462,539	363,908	522,320	158,412	620,951
OHIO	586,622	226,715	477,752	251,037	837,659
OKLAHOMA	48,738	49,900	135,425	85,525	134,263
OREGON	165,956	29,417	62,711	33,294	199,250
PENNSYLVANIA	61,567	55,649	97,249	41,600	103,167
RHODE ISLAND	202	29	85	56	258
SOUTH CAROLINA	67,615	45,021	89,195	44,174	111,789
SOUTH DAKOTA	269,223	291,794	547,097	255,303	524,526
TENNESSEE	122,121	84,209	196,481	112,272	234,393
TEXAS	632,446	268,639	1,031,115	762,476	1,394,922
UTAH	6,250	2,095	5,215	3,120	9,370
VERMONT	1,206	32	399	367	1,573
VIRGINIA	70,950	41,624	77,371	35,747	106,697
WASHINGTON	654,552	79,118	164,088	84,970	739,522
WEST VIRGINIA	1,387	1,968	2,458	490	1,877
WISCONSIN	210,392	146,440	291,789	145,349	355,741
WYOMING	8,560	7,260	14,692	7,432	15,992

Note: Includes 40 crops identified in Table 14 summed by state.

Table 16: No Herbicide Use, Crop Impacts by State (% Yield Change)	
State	
ALABAMA	Cotton –25, peaches –10, peanuts –75, soybeans –45, tomatoes –30
ARIZONA	Corn –23, cotton –30, lettuce –13, sorghum –14, wheat –15,
ARKANSAS	Apples –15, corn –48, cotton –40, rice – 53, soybeans –80, tomatoes –20
CALIFORNIA	Broccoli – 13, carrots –45, cotton –17, lettuce –13, onions –35, tomatoes –20
COLORADO	Corn –20, dry beans –23, onions –23, potatoes –7, sugarbeets –10, wheat –6
CONNECTICUT	Peaches –12, sweet corn –12
DELAWARE	Corn –45, potatoes –20, soybeans –35, sweet corn –30, wheat –50
FLORIDA	Cotton –50, peanuts –33, potatoes –30, strawberries –55, sweet corn –17
GEORGIA	Cotton –65, onions –20, peaches –25, peanuts –60, soybeans –35
IDAHO	Corn –35, dry beans –25, hops –25, onions –15, potatoes –35, sugarbeets –40
ILLINOIS	Corn –22, green beans –10, potatoes –5, sorghum –15, soybeans –22
INDIANA	Corn –15, cucumbers –59, mint – 58, soybeans –15, tomatoes –23
IOWA	Corn –25, soybeans –29, wheat –5
KANSAS	Corn –10, dry beans –12, sorghum – 15, soybeans –15, wheat –10
KENTUCKY	Corn –15, sorghum –10, soybeans –28, wheat –8
LOUISIANA	Cotton –10, rice –53, sugarcane –44, sweet potatoes –30
MAINE	Apples –45, blueberries –67, potatoes –15, sweet corn –15
MARYLAND	Apples –9, corn –31, peaches –14, soybeans –25, tomatoes –15, wheat –9
MASSACHUSETTS	Cranberries –50, potatoes –10, sweet corn –15, tomatoes –30
MICHIGAN	Apples –35, asparagus –50, green beans –60, potatoes –50, soybeans –35
MINNESOTA	Corn –15, dry beans –10, green peas –15, soybeans –10, wheat –30
MISSISSIPPI	Corn –39, cotton –40, rice – 53, soybeans –61, sweet potatoes –20
MISSOURI	Corn –30, cotton –40, grapes –25, soybeans –45, wheat –15
MONTANA	Corn –13, potatoes –15, sugarbeets –11, wheat –30
NEBRASKA	Corn –12, dry beans –25, potatoes –13, sorghum –13, soybeans –15
NEVADA	Potatoes –30, wheat –25
NEW HAMPSHIRE	Apples –5, sweet corn –15
NEW JERSEY	Cucumbers –50, lettuce –50, peaches –50, soybeans –55, spinach –50
NEW MEXICO	Corn –20, cotton –32, onions –15, peanuts –23, wheat –10
NEW YORK	Apples –17, grapes –12, green beans –18, potatoes –30, sweet corn – 20
NORTH CAROLINA	Cotton –70, cucumbers –25, peanuts –66, soybeans –21, sweet potatoes –20
NORTH DAKOTA	Canola –45, corn –10, potatoes –9, sugarbeets –24, wheat –30
OHIO	Corn –34, potatoes –52, soybeans –32, strawberries –35, tomatoes –25
OKLAHOMA	Corn –15, cotton –25, peanuts –40, sorghum –10, soybeans –20, wheat –5
OREGON	Grapes –15, green beans –30, mint –58, strawberries –25, sweet corn –15
PENNSYLVANIA	Apples –20, corn –10, grapes –25, potatoes –22, sweet corn –20
RHODE ISLAND	Apples –10, potatoes –20
SOUTH CAROLINA	Cotton –30, peaches –40, peanuts –52, soybeans –23, tomatoes –15
SOUTH DAKOTA	Corn –15, potatoes –21, sorghum – 19, soybeans –18, sunflowers –16
TENNESSEE	Apples –27, cotton –25, soybeans –30, tomatoes –27, wheat –15
TEXAS	Carrots –25, corn – 46, cotton –30, onions –25, peanuts –33, sorghum –45
UTAH	Corn –35, dry beans –29, onions –22, potatoes –27, wheat –22
VERMONT	Apples –17, sweet corn –15
VIRGINIA	Corn –22, cotton –17, peanuts –22, soybeans –18, tomatoes –40
WASHINGTON	Apples –8, asparagus –55, green peas –20, potatoes –55, wheat –23
WEST VIRGINIA	Apples –12, corn –5, peaches –25, wheat –17
WISCONSIN	Corn –10, green peas –12, potatoes –33, soybeans –15, sweet corn –15
WYOMING	Corn –20, dry beans –23, sugarbeets –10, wheat –6

Note: Selected impacts only.

Table 17: No Herbicide Use, Crop Production Volume Impact by State	
	Production (Million lbs)
State	***Loss***[1]
ALABAMA	826
ARIZONA	482
ARKANSAS	10,833
CALIFORNIA	9,003
COLORADO	2,241
CONNECTICUT	4
DELAWARE	801
FLORIDA	4,297
GEORGIA	2,476
IDAHO	9,424
ILLINOIS	26,121
INDIANA	9,941
IOWA	31,012
KANSAS	5,447
KENTUCKY	2,106
LOUISIANA	16,361
MAINE	294
MARYLAND	1,317
MASSACHUSETTS	81
MICHIGAN	9,800
MINNESOTA	13,552
MISSISSIPPI	3,956
MISSOURI	11,832
MONTANA	1,890
NEBRASKA	10,368
NEVADA	67
NEW HAMPSHIRE	2
NEW JERSEY	442
NEW MEXICO	320
NEW YORK	1,181
NORTH CAROLINA	2,652
NORTH DAKOTA	9,527
OHIO	11,950
OKLAHOMA	607
OREGON	2,273
PENNSYLVANIA	878
RHODE ISLAND	2
SOUTH CAROLINA	708
SOUTH DAKOTA	5,992
TENNESSEE	1,756
TEXAS	10,158
UTAH	112
VERMONT	5
VIRGINIA	886
WASHINGTON	9,427
WEST VIRGINIA	21
WISCONSIN	3,796
WYOMING	235

Note: Includes 40 crops identified in Table 13 summed by state.

[1] Loss without herbicides.

Table 18: No Herbicide Use, Labor for Hand Weeding by Crop				
Crop	***Acres (000)***[1]	***Hours/A***[2]	***Total Hours (000)***	***Total Laborers***[3]
ALMONDS	452	7	3,164	19,775
APPLES	271	20	5,420	33,875
ARTICHOKES	5	23	115	719
ASPARAGUS	70	5	350	2,188
BLUEBERRIES	23	5	115	719
BROCCOLI	70	20	1,400	8,750
CANOLA	1,479	0	0	0
CARROTS	119	14	1,666	10,412
CELERY	25	60	1,500	9,375
CITRUS	1,039	0	0	0
CORN	74,237	5	371,185	2,319,906
COTTON	14,998	13	194,974	1,218,588
CRANBERRIES	32	20	640	4,000
CUCUMBERS	35	30	1,050	6,562
DRY BEANS	1,416	16	22,656	141,600
GRAPES	698	8	5,584	34,900
GREEN BEANS	202	12	2,424	15,150
GREEN PEAS	204	12	2,448	15,300
HOPS	34	35	1,190	7,438
HOT PEPPERS	31	60	1,860	11,625
LETTUCE	190	38	7,220	45,126
MINT	93	18	1,674	10,462
ONIONS	147	64	9,408	58,800
PEACHES	100	6	600	3,750
PEANUTS	1,497	10	14,970	93,563
POTATOES	1,178	10	11,780	73,625
RASPBERRIES	11	43	473	2,956
RICE	3,268	0	0	0
SORGHUM	9,329	0	0	0
SOYBEANS	71,141	5	355,705	2,223,156
SPINACH	14	20	280	1,750
STRAWBERRIES	18	30	540	3,375
SUGARBEETS	1,344	15	20,160	126,000
SUGARCANE	977	25	24,425	152,656
SUNFLOWERS	2,520	0	0	0
SWEET CORN	660	5	3,300	20,625
SWEET POTATOES	69	24	1,656	10,350
TOMATOES	394	37	14,578	91,112
WHEAT	32,789	2	65,578	409,862
WILD RICE	2	0	0	0
TOTAL	221,181	(5)	1,150,088	7,188,050

[1] From Table 5. Acres currently treated with herbicides.
[2] From Table 12.
[3] Calculated by dividing the total number of hours by 160, which is the equivalent to the number of hours needed in a four-week period.

Table 19: No Herbicide Use, Labor for Hand Weeding by State		
State	***# Hours (000)***	***# Laborers***
ALABAMA	11,290	70,566
ARIZONA	5,723	35,771
ARKANSAS	28,751	179,695
CALIFORNIA	43,990	274,940
COLORADO	11,107	69,422
CONNECTICUT	50	317
DELAWARE	1,714	10,713
FLORIDA	16,201	101,261
GEORGIA	27,633	172,711
IDAHO	11,398	71,240
ILLINOIS	105,573	659,836
INDIANA	56,553	353,462
IOWA	108,719	679,500
KANSAS	33,861	211,636
KENTUCKY	11,057	69,111
LOUISIANA	27,770	173,565
MAINE	780	4,875
MARYLAND	4,891	30,574
MASSACHUSETTS	356	2,230
MICHIGAN	30,114	188,216
MINNESOTA	80,984	506,150
MISSISSIPPI	28,795	179,971
MISSOURI	41,908	261,928
MONTANA	8,702	54,393
NEBRASKA	67,309	420,682
NEVADA	68	428
NEW HAMPSHIRE	42	263
NEW JERSEY	1,343	8,396
NEW MEXICO	3,529	22,059
NEW YORK	6,246	39,041
NORTH CAROLINA	25,280	158,004
NORTH DAKOTA	43,344	270,900
OHIO	38,873	242,957
OKLAHOMA	10,243	64,024
OREGON	5,457	34,110
PENNSYLVANIA	8,083	50,519
RHODE ISLAND	8	53
SOUTH CAROLINA	7,696	48,104
SOUTH DAKOTA	42,204	263,777
TENNESSEE	16,730	104,567
TEXAS	87,632	547,706
UTAH	433	2,710
VERMONT	42	264
VIRGINIA	6,660	41,630
WASHINGTON	13,919	86,997
WEST VIRGINIA	222	1,388
WISCONSIN	24,305	151,910
WYOMING	1,401	8,760

Note: Includes 40 crops identified in Table 18 summed by state.

Table 20: Cropland Erosion Rates by State					
		Tons/Acre Yr.[1]			
State	***No-Till Acres***[2]	***Cultivated***	***Non-Cultivated***	***Difference***	***Erosion prevented by No-Till (million lbs)***
ALABAMA	434,916	6.7	.5	6.2	5,392
ARIZONA	4,100	.7	.2	.5	4
ARKANSAS	755,413	3.5	.6	2.9	4,381
CALIFORNIA	12,692	.7	.5	.2	5
COLORADO	513,435	1.7	.2	1.5	1,540
CONNECTICUT	3,825	5.6	.7	4.9	37
DELAWARE	233,775	2.0	.4	1.6	748
FLORIDA	53,856	1.8	.5	1.3	140
GEORGIA	505,112	5.9	.3	5.6	5,657
IDAHO	233,781	3.4	.4	3.0	1,402
ILLINOIS	6,961,627	4.1	.6	3.5	48,731
INDIANA	4,908,432	3.0	.9	2.1	20,615
IOWA	5,056,840	4.9	.8	4.1	41,466
KANSAS	3,154,908	2.2	.4	1.8	11,357
KENTUCKY	1,784,529	4.4	1.2	3.2	11,420
LOUISIANA	240,186	3.3	.6	2.7	1,297
MAINE	672	3.9	.3	3.6	4
MARYLAND	686,162	4.4	1.2	3.2	4,391
MASSACHUSETTS	4,080	4.5	.1	4.4	35
MICHIGAN	1,387,500	2.0	.5	1.5	4,162
MINNESOTA	457,790	2.1	.3	1.8	1,648
MISSISSIPPI	791,984	5.3	1.2	4.1	6,494
MISSOURI	3,170,081	5.6	.7	4.9	31,066
MONTANA	1,115,249	1.9	.3	1.6	3,568
NEBRASKA	3,468,978	2.9	.5	2.4	16,651
NEVADA	0	.2	0	.2	0
NEW HAMPSHIRE	600	3.5	.4	3.1	3
NEW JERSEY	84,277	5.6	.6	5.0	842
NEW MEXICO	110,931	.9	.1	.8	177
NEW YORK	114,627	3.9	.7	3.2	733
NORTH CAROLINA	1,456,624	5.0	1.0	4.0	11,652
NORTH DAKOTA	1,906,711	1.4	.3	1.1	4,194
OHIO	4,204,204	2.6	1.4	1.2	10,090
OKLAHOMA	497,806	2.8	.5	2.3	2,289
OREGON	165,115	3.1	.4	2.7	891
PENNSYLVANIA	515,273	5.1	1.2	3.9	4,019
RHODE ISLAND	108	3.5	1.8	1.7	0
SOUTH CAROLINA	354,605	3.2	.7	2.5	1,773
SOUTH DAKOTA	2,996,322	2.0	.2	1.8	10,786
TENNESSEE	1,410,364	7.7	.6	7.1	20,027
TEXAS	447,452	2.6	.8	1.8	1,610
UTAH	11,298	1.6	.2	1.4	31
VERMONT	3,550	3.1	.7	2.4	17
VIRGINIA	665,482	5.9	1.5	4.4	5,856
WASHINGTON	342,494	4.7	.6	4.1	2,808
WEST VIRGINIA	47,655	4.3	.8	3.5	33
WISCONSIN	876,734	3.7	1.2	2.5	4,383
WYOMING	28,869	1.1	.1	1.0	58
TOTAL	52,181,024				304,483

Note: Sheet and Rill Erosion

[1] Source: [342]
[2] Source: [72], data for 2000.

4.0 Summary and Conclusions

Every year, U.S. growers choose herbicides as the primary method to kill weeds that would otherwise significantly lower yields. An average U.S. cropland acre is treated with two pounds of herbicide active ingredient costing $30/acre.

If U.S. farmers employed an additional 7 million hand weeders and increased cultivation, overall crop production would decline by 21 percent, which is equivalent to 288 billion pounds of food and fiber. If farmers could not pass along their increased costs to buyers, then the $7.7 billion increased production cost combined with lost production valued at $13.3 billion would result in reduced grower net income of $21 billion, or 40 percent of the total net income of American farmers. NCFAP researchers made no attempt to estimate the number of farmers who would stop producing crops given this reduction in income.

To estimate the value of herbicides, NCFAP simulated their nonuse and replacement with available alternatives. Another approach would be to simulate the amount of labor necessary to prevent any yield loss. However, the large estimated labor requirement (70 million workers) would have been of limited use in policy discussions.

Herbicides are essential if the U.S. is to maintain current yields. Even though there is an equally effective alternative for most crops, hand weeding, cost and labor scarcity mean it is unlikely growers could substitute enough hand labor to maintain yields. The Environmental Protection Agency regularly approves emergency herbicide registrations because growers cannot afford to use hand labor to remove weeds.

NCFAP assigned sufficient hand weeding to prevent yield loss to four crops. This assignment, however, was made merely to illustrate that hand labor could prevent yield losses. In actuality, the growers of celery, citrus, hot peppers and raspberries would be unlikely to employ the weeders specified, and yield losses would occur. It is equally unlikely that growers of other crops in the study would employ the number of workers specified because the workers needed for weeding is seven times the current number of farm workers. As a result, yield losses would be higher for all the studied crops.

Therefore, the NCFAP estimates represent the minimum economic impact of the nonuse of herbicides.

No consumer price increases and no food shortages are estimated. The estimated losses could be made up with increased imports meaning a $13.3 billion worsening of the trade balance.

Herbicide use is only 60 years old and yet, societal changes have occurred that make it impossible to return to previous weed control practices. Migration of workers from rural areas has created shortages of farm workers. The average wage rate for farm workers has increased by 7000 percent in the last 60 years. Farmers who paid $10/acre for hand weeding in the 1940s would face a labor cost of $700/acre at today's rates. The use of herbicides at $30-50/acre remains the most cost-effective alternative. To put herbicide use in perspective, research examining weed control practices of organic growers shows they often do not employ enough laborers to prevent yield losses. A vast expansion of organic crop acreage in the US is unlikely due to the high costs of hand weeding. In fact, organic growers cite weed control without herbicides as their biggest problem. Herbicides are used on 220 million acres of cropland while organic cropland totals 1 million acres. The amount of labor necessary for a vast expansion of organic growing is not available.

Herbicide use has enabled U.S. farmers to significantly reduce their use of tillage for weed control. The reduction in tillage has resulted in less erosion. Without herbicides, U.S. growers would no longer be able to practice no-till crop production. The abandonment of no-till farming would result in an increase of 304 billion pounds of soil erosion.

This study is the first comprehensive documentation of the role that herbicides play in U.S. crop production. Herbicide use is routine for farmers and poorly understood by the public and the media. This report is meant to stimulate discussion of the importance of herbicides and to clearly indicate the choices and consequences of farming without their use.

5.0 Appendices A.1 – A.40

A.1 Almonds

Maintaining an orchard floor free of weed growth has many advantages for almond production. In addition to competing with almond trees for water and nutrients, weeds also interfere with the harvesting of nuts, which are picked up off the soil surface after being knocked from the tree [195]. Prior to the introduction of herbicides for weed control, it was common practice to disk in both directions with heavy equipment that tended to compact the soil, decreasing water penetration [196]. Decreased water penetration increased the amount of runoff water in orchards and led to soil erosion problems. Disking also results in mechanical injury to the lower trunk, making the tree susceptible to diseases [196]. In addition, disking cuts feeder roots in the top six inches of soil; thus, the tree cannot use the rich supply of nutrients, water and oxygen in this area [196].

Research began in 1958 for herbicides in almonds with two purposes: to increase water penetration and to eliminate the need to hand hoe weeds from around the base of trees [197]. The use of herbicides substituted for 16 cultivations (including five hours of labor) and two hours of additional hand labor for hoeing [197]. In addition, one less irrigation was necessary once tillage was eliminated. Grower savings of $21/A were reported (labor was priced at $1.65/h) [197]. Reduced tillage meant less dust, which reduced spider mite problems. Harvesting and hulling were completed faster due to fewer problems with dirt and stones [198].

Organic almond growers typically plant a cover crop that requires a post-harvest irrigation ($14/A), mow weeds three times during the season ($22/A) and use labor for hoeing and mowing (7 hours/A) [199]. In 1965, it was estimated that California almond growers applied herbicides to 27% of the state's acreage, while in 1999, 86% of the acreage was treated [258] [14]. It has been estimated that without herbicide use, California almond yields would decline by 5% [5].

A.2 Apples

Weeds compete with apple trees for water, light, nutrients, and space. Weeds can harbor insect, disease and rodent pests that can adversely affect apple trees [331]. The girdling of apple trees by field mice is a common problem. Since these species of mice will seldom cross a bare area to feed, it is desirable to remove all vegetation at the base of trees to help reduce the possibility of girdling. Prior to the development of herbicides, apple growers maintained the bare area by slow and costly hand labor methods [332]. At least two and sometimes three hoeings a year were needed [333]. Mechanical cultivation and mowing were also used to lessen weed cover and competition. During every cultivation, running the cultivator close to the trees raised the risk of injuring or destroying an occasional tree. The scarcity and increased cost of labor resulted in research into chemical weed control in apple orchards [335].

Residual herbicides maintained a weed-free band down the tree row for approximately six months [335]. Research showed that mouse injury could be eliminated with herbicide treatment in comparison to higher incidences with cultivation only (86% injury) or cultivation and three hand hoeings (12% injury) [334] [332]. Research also showed increased apple yields in herbicide-treated areas in comparison to tilled areas due to less root pruning and less trunk injury. Studies have shown that apple trunk girth, shoot length and yields are higher with herbicide treatments than with cultivation [331]. A recent Michigan State University study concluded that without herbicides, apple growers would be forced to switch to more costly, less effective methods for weed control [337]. Damage from mechanical weeding was estimated to reduce apple tree yields by 10%. Another alternative would be to apply mulch in the orchard (at $275/A). The mulch cover would necessitate increased irrigation water usage in the Northwest, as well as a five-fold increase in the use of rodenticides to kill mice [53].

Weed control is one of the biggest challenges in organic apple production due to the high cost of alternative methods when compared to herbicides [338]. A Colorado organic apple grower reported that mice girdled 1000 trees on their farm in 1999 [307]. A cost of production budget for organic apples in California includes 20 hours of hand weeding and 2 diskings per acre for weed control [338].

In 1964, it was estimated that 15% of U.S. apple acreage was treated with herbicides [376]. USDA surveys indicate that approximately 63% of U.S. apple acreage has been treated with herbicides annually in recent years [14]. The proportion of apple acreage treated with herbicides has increased in recent years as growers have increased plantings of dwarf trees (see Figure A1).

Growers often use high-density plantings in new orchards. High-density plantings are less competitive with weeds than traditionally larger trees and make weed control more important [331]. The new orchards typically have 200 to 1500 trees per acre compared with older orchards, which had 50 to 80 trees per acre. In older orchards with larger trees, many growers tolerated weeds. Research demonstrated the importance of weed control on apple tree growth in the new high-density orchards [371]. The high-density orchards with trees 8 to 10 feet tall are designed to utilize available soil and water resources fully; thus there is less tolerance for weeds. Smaller trees with smaller roots are more sensitive to weed pressure. Experiments in high-density apple plantings resulted in an average yield increase of 32% in the herbicide-treated plots, in comparison to the mowed plots [336]. It has been estimated that without herbicides, U.S. apple production would decline by 15% [5].

A.3 Artichokes

Artichoke production systems are classified as either perennial or annual. Perennial artichokes are harvested for 5 to 10 seasons before replanting. Annual artichokes are harvested for one season. Approximately 80% of California's artichokes are perennial [327]. There are two important times when herbicides are used to control weeds in perennial artichokes: planting a new field, and after irrigation ditches are made [328]. Newly planted fields need to be as weed-free as possible to ensure a good start for the plants. Most growers apply a residual herbicide at planting. Standard production practices call for new artichoke stands to be heavily watered for 30 to 60 days after transplanting. The wet environment is not only conducive to weed growth, but it also impedes hand weeding [330]. Weedy shoulders are slippery, creating a safety hazard to the harvesting crew. The second important time is after winter rains when ditches are made in perennial artichokes to assure proper drainage. Harvesting requires a walking path on the shoulders of the ditches. Weedy shoulders slow down the harvesting process and the drying rate of artichoke beds. During the rainy season, wet soils make mechanical cultivation difficult and some growers apply herbicides [329]. Perennial artichoke is planted at wide row spacing, which permits cultivation in two directions, and is cross-cultivated 4-5 times [328]. Prior to the development of herbicides, the typical perennial acre was cultivated 7 times [369]. Annual artichoke is planted more densely and cultivated in only one direction. A larger area is left uncultivated, which requires herbicide application or hand weeding [330].

A recent experiment determined that perennial artichokes would produce equivalent yields if 4 additional hours of hand weeding/A substituted for herbicides [330]. However, in annual artichoke production, yields were 32% lower even with an additional 42 hours of hand weeding/A as a substitute for herbicides [330].

USDA surveys indicate that approximately 58% of California's artichoke acres are treated with herbicides [16]. Assuming that herbicide-treated artichoke acres are divided equally between perennials and annuals, this implies a need for 23 additional hours of hand weeding and a yield decline of 16% without herbicides.

A.4 Asparagus

Asparagus is a perennial vegetable crop. It takes about three years for asparagus to develop from seed into a producing plant. Asparagus crowns can be productive for 20 years. Asparagus spears are usually hand harvested every one to five days in the growing season.

Asparagus competes very poorly against weeds because the crop does not produce much shade until late in the season. Weeds growing around spears make harvest very difficult, since harvesters cannot see the proper spears to be cut [207]. Prior to the introduction of herbicides, weed control in asparagus was accomplished with 4-6 cultivations [205]. However, cultivating during the cutting season causes the loss of 5 to 7 days of spear production [206]. Disking up the field causes reduction in the vegetative stalks and can be reflected in reduced yield in subsequent years [377].

The use of herbicides offered relief from this mechanical injury. Early research with residual herbicides resulted in weed-free beds for 4 weeks following application, with no need for cultivation or hand hoeing [208]. Weed control has been identified as the most serious challenge facing organic asparagus growers [209]. USDA surveys in the 1990s indicate that from 81-91% of U.S. asparagus acreage is treated with herbicides [16]. It has been estimated that without herbicides, U.S. asparagus production would decline by 55% [5].

A.5 Blueberries

Lowbush blueberry fields in Maine have been developed from naturally occurring stands. Through management of this wild acreage, commercial blueberry production reached 10 million pounds annually in 1927. Weeds were identified as a major factor that limited yield in 1946 and were still a major concern in a 1974 survey [210]. Weed growth not only lowered blueberry yield through competition but also made harvesting difficult with 10-30% of the crop left behind [236]. The inability to control weeds also resulted in growers' unwillingness to fertilize blueberries, since the fertilizer resulted in dense growth of weeds [236].

The registration of terbacil in the 1970's provided effective control of grasses and sedges, and resulted in significant yield increases when combined with increased fertilizer use [212] [213]. The subsequent registration of hexazinone in the early 1980's provided effective control of grasses, herbaceous, and woody weed species in low bush blueberry fields [213]. As a result of improved weed control, research demonstrated that use of hexazinone increased blueberry yields by 56% [213] [214]. Since the introduction of hexazinone in 1983, blueberry production in Maine has more than tripled, from an average of 20 million pounds per year to over 75 million pounds per year (see Figure A2). The consumption of blueberries in the diet of Americans increased significantly following the increased production in Maine (see Figure A3). In addition to reduced weed competition, hexazinone has facilitated increased use of fertilizer. Approximately 95% of Maine's wild blueberry crop is treated with herbicides [74].

A study comparing organic and conventional blueberry farms in Maine revealed that organic yields were 75% lower than the conventional farm yields [215]. Without herbicides, Maine's blueberry production would decline by 67% [74].

A.6 Broccoli

Broccoli is a direct-seeded crop. Although broccoli germinates rather quickly, it is very susceptible to competition from weeds during the germination and early growth stages. Prior to the development of synthetic chemical herbicides, weed control in California broccoli fields was accomplished through repeated cultivations and hand weeding with short-handled hoes. These practices were very costly, and resulted in lower yields from root damage and inadvertent loss of plants. In the late 1960s, it was estimated that hand weeding broccoli fields cost about $40/A (20 hours/A@$2/HR). The scarcity and rising costs of labor spurred research into chemical herbicides for broccoli [249]. Research demonstrated that the herbicide nitrofen could be used safely over the top of broccoli plants to control emerged weeds [249]. With the development of nitrofen, broccoli became the first seeded crop that could be planted to a stand with minimal hand weeding. When herbicides replaced hand weeding, broccoli growers reported a savings of $35/acre and a 30% increase in yield [320].

Following the cancellation of nitrofen, broccoli growers had limited weed control choices. In 1981, EPA estimated that broccoli growers might incur hand weeding costs of up to $100/A (20 hours/A @ $5/HR) [250]. Broccoli growers substituted by increasing hand weeding and increased the use of other herbicides (DCPA, trifluralin) for nitrofen. Many broccoli growers stopped using herbicides (only 51% of broccoli acreage is treated with a herbicide). These growers substituted liquid nitrogen fertilizer for killing weeds. These fertilizers have contact weed control properties, and broccoli has a protective waxy surface (cuticle) that protects it from damage [251]. At an increased fertilizer rate of 200 pounds per acre, weed control is effective, although the fertilizer treatment is not registered as an herbicide [252]. An organic broccoli grower in Rhode Island reports the need for 22 hours of hand weeding per acre following 4 cultivations [299]. It has been estimated that without herbicides, California and Arizona broccoli production would decline by 13% and 24%, respectively [5].

A.7 Canola

Canola is an edible type of rapeseed that was developed in Canada in the 1970s. Canola oil is usually blended with other vegetable oils for the production of various solid and liquid cooking oils and salad dressings. Canola was first planted in the U.S. in the late 1980s.

Weeds are the most limiting factor in canola production. Weeds affect canola in two ways. First, weeds reduce yields by competing for available resources. Uncontrolled weeds, such as wild mustard, have been reported to reduce canola yields ranging from 19 to 77% [200]. Second, weed seeds such as wild mustard reduce the quality by contaminating canola seed. Since canola is a shallow-seeded crop, the use of a rotary hoe or harrow for weed control is discouraged. These tillage tools can injure or destroy canola seedlings [201]. Canola is commonly seeded in narrow rows. In-crop cultivation is not a viable alternative. Canola is a cool season crop that is most productive when seeded early in the spring. Broadleaf weeds and annual grasses that compete with the canola germinate and emerge along with the canola seedlings. Although delayed seeding and/or tillage can reduce weed abundance, these practices result in lower canola yields due to non-optimal planting dates. At the time of its introduction in the U.S., very few herbicides were registered for canola. Canola production was limited in the U.S. because growers were unwilling to expand acreage into areas with significant weed problems that could not be controlled. In addition, the early 1990s were a period of rapid infestation by Canada thistle in canola-growing states, which was not controllable by the previously registered herbicides. Canola growers petitioned EPA for the registration of effective herbicides, citing the potential loss in canola yield of 24 to 35% from Canada thistle. The registration of effective herbicides resulted in a 59% expansion of canola acreage, as the herbicides resulted in reduced weed competition and lower dockage in the harvested canola seed [202] (see Figure A4). Total U.S. canola production increased by 75% [1].

Research demonstrated an increase in canola yield of 73-80% as a result of using effective herbicides, in comparison with a weedy check [203] [204]. It is estimated that 99% of canola acreage is treated with herbicides [253].

A.8 Carrots

Prior to the introduction of synthetic chemical herbicides, carrot growers controlled weeds with cultivation, hand weeding with short-handled hoes and the use of oil to kill emerged weeds. Cultivation can only be used between the rows of plants, and weeds growing in the row are uncontrolled. Carrots required 28 hours per acre for weeding and hoeing in California in the 1930s [193]. High re-registration costs resulted in the voluntary cancellation of oil for carrots. Short-handled hoes were banned in California in the 1960s. Oil was used at approximately 50 gallons per acre; oil use was generally not harmful to carrots and killed a broad spectrum of weeds [19].

Early research with synthetic chemicals, particularly linuron (at 1 lb/A), demonstrated less expensive weed control in comparison to the use of oil and hand weeding [20] [21]. Carrot yields did not dramatically increase following the widespread use of herbicides, since the hand weeding with short-handled hoes and oil treatments were effective (See Figure A5). Mechanical cultivation would be the primary substitute for herbicides, and therefore it was assumed that hand weeding would be used only as a small-scale replacement [17]. Organic carrot growers report that the biggest cost in producing organic carrots is weed control, with primary reliance on hand weeding and cultivation [22]. USDA has recently estimated that herbicides are used on 98% of U.S. carrot acreage, and that without herbicides, U.S. production of carrots would decline by 48% [17].

A.9 Celery

In the 1940s, it was reported that production costs for celery were higher than any other field-grown vegetable crop in California [339]. Until the middle 1960s, weed control was one of the largest production costs for California celery growers. Each celery acre required 30 to 60 hours of weeding, with crews using short-handled hoes [340]. Research demonstrated that herbicides in celery fields would provide greater than 90% control of troublesome weed species [341]. Celery yields with the herbicide treatments were equivalent to the hand weeded plots [340]. Approximately 85% of US celery acreage receives herbicide treatments [16].

A. 10 Citrus

After World War I, heavy tractor-drawn equipment for mechanical cultivation of weeds became increasingly common in California's citrus orchards. However, in most orchards the frequent traffic of heavy equipment caused a gradual deterioration in soil structure. The result was decreased water penetration and damaged roots, which reduced tree growth and productivity. Cultivation destroyed citrus feeder roots in the top layers of soil, and created a soil hardpan above the remaining deeper roots, which were cut off from nutrients and water [50]. Damage to roots provided entryways for disease organisms.

In the 1940s, experiments began using light petroleum oils for weed control as an alternative to mechanical cultivation. The use of non-tillage in citrus orchards was rapidly adopted in California and is regarded as the most fundamental change in soil management in the history of citrus production [41]. Citrus groves in California were treated with 90 gallons of oil per acre [41]. Oil kills weeds present at the time of treatment and requires repeated applications [42]. The first residual herbicide registered in citrus was monuron in 1955, which was followed by simazine and diuron. Research demonstrated that two applications to the soil of the residual herbicides in combination provided yearlong control of most annual weed species [44]. Post emergence contact herbicide applications are made to control weeds missed by the residual compounds. Organic citrus growers in California control weeds with hand weeding, mechanical mowing, and cover crop mulches. Organic orchards are typically weeded three times each year, with a total use of 6 hours of labor [385].

Florida's warm and humid climate offers a very conducive environment for continuous germination of weed seeds and vigorous growth. Frequent irrigation and nutrient applications further enhance the weed problem in citrus groves, and uncontrolled weeds use a sizeable portion of nutrients and water, resulting in poor tree growth and reduced yields. Prior to herbicide use, Florida citrus groves were mechanically cultivated and hand hoed [46]. Eight to nine mechanical weedings and 2-3 hand weedings were required per acre [47] [52].

Chemical weed control became widespread in Florida in the late 1960s. Adoption of herbicide technology enabled growers to significantly reduce the costs of labor in Florida groves [48]. Florida research demonstrated that significantly better tree growth, earlier production, and less physical damage to trees occurred under herbicide programs compared to tillage programs [49]. Research showed that non-tilled groves under a chemical weed control program are 1 to 2 C warmer than trees under cultivation or sod [51]. This degree of warming is sufficient to significantly improve tree survival during cold nights. Therefore, citrus growers embraced chemical weed control, not only as a yield-improving measure but also for freeze protection. The benefits of this practice are acknowledged by the Federal Crop Insurance Corporation, in the form of discounted tree insurance premiums to growers who use chemical weed control with no tillage.

A survey of Florida organic citrus growers determined that weeds are considered the single most important problem in organic citrus production [55]. Mechanical cultivation (up to 5 times) and hand weeding (up to 4 times) are required for organic production.

In 1964, it was estimated that 5% of U.S. citrus acreage was treated with herbicides [376]. A 1971 survey indicated that 22 % of U.S. citrus acreage was treated with herbicides; surveys conducted since 1993 indicate that 84-95% of U.S. citrus acres are treated annually with herbicides [14] [173]. A recent study, projecting the economic impacts of eliminating herbicide use in citrus, estimates that yields would remain unchanged in California and Florida [53]. Increased cultivation would occur in California without herbicides; in order to maintain yields, the use of fertilizer and irrigation water would have to double [53]. Thus, without herbicides, California growers would have to cultivate 8 times and apply an additional 30 acre inches of water and an additional 88 pounds of fertilizer per acre [54]. In Florida, herbicides would be replaced with an additional 8 mowings per year and with an additional 67 hours of labor for hand hoeing. The increased costs of the no-herbicide scenarios were estimated at $400/A in Florida, due to mowing and increased hand labor and, $359/A, in California due to increased use of fertilizer, irrigation and cultivation [53].

A.11 Corn

An 18-year study in the early 1900s demonstrated that without weed control, corn yields would be reduced to zero in some years and would generally be about 80% lower than in plots where weeds were controlled [220]. A 1912 USDA study summarized the results of 125 experiments from the late 1800s and early 1900s, concluding that the only benefit from cultivating corn was weed control [230]. In the years prior to the use of herbicides, common practice for weed control in corn was to cultivate 4 to 5 times. In order to facilitate complete cultivation of cornfields, the corn plants were planted far enough apart to allow for cultivation on all four sides of each plant [221]. Certain weeds were poorly controlled by cultivation and required hand labor for removal, often by family children [372] [373] [374]. At times, cultivation lowered corn yields due to root pruning [222]. One limitation on cultivation's effectiveness is the inability to cultivate in a timely fashion due to wet conditions [223]. A reduction of corn yield of .57 bu/A/day was expected with each day's delay in the cultivation operation, with a 5-day delay being common [224]. In river bottomlands, where the soil was often too wet for timely cultivation, corn crops were often lost because weeds took over [225]. In some areas, farmers stopped growing corn because of weed problems [226].

The introduction of 2,4-D in the late 1940s provided corn growers with an effective post emergence control of broadleaf weeds, and led to a reduction of cultivation. Initially, chemical weed control in corn replaced two cultivations [315]. Herbicide use in corn improved yields 15-25%, compared to cultivation due to control of weeds in the row of plants and less damage to corn plants due to root pruning [316]. 2,4-D use is credited with saving some bottomland cornfields from abandonment [225]. One report from 1947 states that one million additional bushels of corn were produced from 18,000 acres of bottomlands in Kentucky as a result of 2,4-D spraying [384]. In 1947, Nebraska corn yield increases of 11-49% were recorded as a result of 2,4-D spraying [384]. In 1959, the introduction of atrazine made it possible for corn growers to control a broad spectrum of weeds with residual pre emergence herbicide treatments, creating further reductions in tillage. Research demonstrated that substituting atrazine for tillage resulted in an 8% increase in corn yield [227]. Average corn plant populations increased from approximately 12,000 plants/a in the 1950s, to 20,000 plants per acre at the end of the 1970s. Corn yields steadily increased in the decades following World War II (see Figure A6). A statistical analysis of the contribution of individual technological improvements to corn yield credited increased herbicide use as accounting for 20% of the increase in corn yields from 1964 to 1979 [229]. In recent years, the typical corn acre was tilled once [152]. Research showed that two hand weedings, totaling 60 hours per acre, would produce corn yields equivalent to herbicide treatments. Since the hoeing would need to be done during a six-week period, a labor force of 18 million people was estimated as the total hand weeding need for corn [317]. Combining 18 hours of hand weeding/acre with cultivation also produced corn yields equivalent to herbicide treatments [317].

Numerous experiments have been conducted over the last ten years examining the effectiveness of alternative cultivation techniques for weed management in corn. Research has shown that if the timing is optimal and enough cultivation trips are made, corn yields can be equal to those in herbicide treated plots. In one experiment, 3 rotary hoeings and 2 cultivations produced corn yields equal to those of normal rates of herbicides [231]. Research has also shown that mechanical cultivation is less effective than herbicides during years when rain prevents timely tilling [232]. In one experiment, corn yields were similar in dry years, but in one year, wet weather caused cultivations to be late, preventing the final cultivation entirely [233]. In that year, mechanical treatments, which had produced equivalent yields to herbicides in dry years, resulted in yields 26% lower than the herbicide treated plots [234]. A cost of production budget for organic corn in the Northeast, based on information from the Rodale Institute, specifies a 13% reduction in corn yield [361]. North Dakota State University has prepared budgets for organic corn, which specify a 25% yield reduction [260].

Figure A7 shows the trend in U.S. corn acreage treated with herbicides. Approximately 7% of the nation's corn acres were treated in 1949. More than 90% of U.S. corn acres have been treated with herbicides since 1976. Nationally, it is estimated that corn yields would decline by 20% without herbicides [5].

A.12 Cotton

Prior to the early 1900s, weeds in cotton were controlled by hand hoeing. In the early 1900s, a combination of 5 to 7 mechanical cultivations and hand hoeing provided adequate weed control [154]. In the 1930s, it was estimated that 33 hours of labor were required for hoeing an acre of cotton [155]. Hand hoeing was generally effective, but the labor needed from year to year fluctuated widely and could exceed 100 hours per acre [157]. In the early 1950s, weed control was the last key needed to complete mechanization of cotton production—following the mechanization of harvest. Prior to 1960, less than 10% of the total U.S. cotton acreage received herbicide treatment, but by 1970, most cotton acreage received herbicide treatment (see Figure A8). The impetus behind this rapidly expanded use was more selective and effective herbicides such as trifluralin and DSMA/MSMA.

Also, the mass exodus of farm workers, who had provided the hand labor for hoeing weeds in cotton, continued to move from rural to urban areas [156]. The prices paid for hand labor in the 1950s and early 1960s increased three to four fold, partially because of the migration of vast numbers of farm workers from southern to northern states [158]. Several individual southern states experienced a net loss of 200,000 to 300,000 farm workers within a decade. This dramatic loss of farm labor caused the price of hoe labor to increase dramatically, and in some localized areas, to be unavailable for cotton. It has been estimated that chemical weed control reduced the labor requirements on 1 million acres of cotton in Mississippi by 20 hours per acre [160]. The hoe labor was budgeted at $.50/hour. In Arkansas and Alabama, research demonstrated that chemical applications could reduce hand labor by 75%, in most instances. This represented a reduction of 30 to 40 hours per acre of hand labor [162] [163]. Research in Georgia demonstrated that chemical weed control was equivalent to 26 hours/A of hand hoeing [164]. Because of the effectiveness of hand hoeing, the switch over to herbicides did not reduce yield losses to weeds, or lead to dramatically increased yields (see Figure A9). In the 1951-1960 time frame, it was estimated that U.S. cotton yield loss to weeds totaled 8% [148]. In 1980, it was estimated that weed interference in U.S. cotton fields reduced cotton production by 7.4% [159].

A preliminary three-year study in California resulted in equivalent yields of organic and conventional cotton [322]. However, in subsequent years the organic yields were 19% lower than the conventional ones [322]. A cost-of-production budget for California organic cotton identifies a need for 9 cultivations and 12 hours of hand weeding per acre [323]. A national survey of organic cotton growers indicated that they control weeds with cultivation and hand weeding [368]. Lower yields and higher costs for weeding are two of the main reasons that organic cotton sells at a higher price [324]. Organic cotton growers identify the greatest research need to be improved weed control [321]. After peaking at 25,000 acres in 1995, U.S. organic cotton acreage has declined to 11,000 [321] (see Figure A10) due to the withdrawal of several large apparel buyers from the organic market [325]. Expansion of organic cotton acreage in the U.S. has been stifled, due to the reluctance of clothing companies to sign contracts with U.S. growers when they can buy organic cotton much cheaper in countries like India and Turkey, where labor costs are significantly lower [326]. A national survey of organic cotton growers indicated that average yield was .9 bales per acre in 2000, which was 30% lower than average U.S. cotton yield [321].

Recent research has shown that it is possible to achieve cotton yields with hand hoeing equivalent to those of herbicide treatments [161]. However, 67 hours per acre was required in Alabama. A recent report from USDA estimated that, without herbicide use, U.S. cotton yield would decline 27%, despite increased cultivation and hand hoeing [165]. A recent report from Texas A&M University estimated that without herbicides, U.S. cotton yields would decline by 17%, despite 5-9 additional cultivations and 5-20 additional hours of hand weeding per acre [95].

A. 13 Cranberries

An individual cranberry vine can be productive for fifty years before replacement is necessary. The leaves of the cranberry plant form a dense mat over the surface. There are no paths through a cranberry bog. Weeds are particularly troublesome in cranberry bogs, since mechanical equipment (such as cultivators) cannot be used for their control [29].

In the early 1900s, cutting with a scythe and hand pulling were the only methods of controlling weeds in cranberry bogs. It was a common sight in the “old days” to see gangs of weeders crawling over the bogs, dragging their weed baskets after them. In those days, weeders were paid about ten cents an hour, and by keeping them continually at work, some beautiful bogs were kept scrupulously clean [30]. In the 1930s, with the rising cost of labor, the realization came that hand weeding, on a large scale, was out of the question. Hand weeding also caused considerable damage to the cranberry plants [31]. Vines and berries were crushed under the workers feet. Among the labor saving methods of weed control discovered in the 1930s, the most generally accepted was the spraying of kerosene oils. Research in the 1930’s indicated that dormant cranberry vines would tolerate heavy dosages of kerosene; but that most grasses, sedges, and rushes would be killed [30]. In the 1950s, over a half a million gallons of kerosene were sprayed annually in Massachusetts cranberry fields [30]. The minimum dosage of kerosene for effective weed control in cranberry bogs is 300 gallons per acre [30]. Significant increases in oil prices in the early 1970s made the continued use of kerosene oils prohibitively expensive for cranberry growers [32]. Another common practice in the 1940s and 1950s was to broadcast spray ferrous sulfate at rates of 3,000 to 8,000 pounds per acre for control of poison ivy, chokeberry and wild bean [31].

The first synthetic chemical herbicide to receive widespread use in cranberries was dichlobenil, which was tested in 1959 and registered in 1965. Research indicated that a single application of 4 lb AI/A would provide six to eight weeks control over a broad spectrum of perennial and annual broadleaf and grassy weeds. In the 1970s, registration was granted for two other synthetic chemical herbicides: norflurazon and napropamide. These two herbicides expanded the list of weeds effectively controlled. Use of the herbicides led to the almost complete eradication of certain weed species from cranberry bogs [33] [34] [35]. The synthetic herbicides largely replaced the use of kerosene and ferrous sulfate, because they were cheaper and more effective [36]. In the early 1970s, the introduction of dichlobenil, norflurazon, and napropamide is credited as the most important factor in the doubling of cranberry yields from 1960-1978 [35] [38] (see Figure A11).

Another major breakthrough in weed control was the registration of glyphosate, used as a herbicide that is wiped on the portion of the weeds that is taller than the cranberry vines. This use of glyphosate controls certain weeds that had not been adequately controlled with the previously registered herbicides [37]. The introduction of glyphosate is credited with a steep increase (50%} in cranberry yields in the early 1980s [35] [38] (see Figure A11). The improved yields led to a doubling of overall volume production of cranberries, as acreage remained the same.

Approximately 95% of U.S. cranberry acreage is treated with herbicides. A recent report estimates that, without the use of herbicides, cranberry yields would likely decline by 50 to 60 percent, as growers would resort to the less effective weed control methods of hand pulling and mowing [39]. The report concludes that without herbicides, up to half of U.S. cranberry growers would eventually go out of business, since it would no longer be profitable to farm when their beds became overwhelmed by weeds in 5 to 10 years [39].

A.14 Cucumbers

The main alternative to herbicides in cucumber fields is mechanical cultivation. However, due to the vining nature of cucumber plants, mechanical cultivation has limited effectiveness. Each successive cultivation is less effective than the previous one, because the uncultivated row area must be increased with each cultivation, as the plant grows larger and the cultivation tool is adjusted away from the row to prevent crop injury [244]. Cultivation must be completed on schedule to control small weeds, and rainy periods often provide opportunity for weeds to grow too large for control by cultivation [244]. Early research with residual herbicides in cucumbers indicated that preplant applications provided 5-7 weeks of control [245]. A three-year experiment comparing herbicides with cultivation indicates cucumber yields were 24% higher in the herbicide treated plots [246]. In states such as Florida, where it is grown as a second crop in fumigated ground covered with plastic, a significant portion of cucumber acreage does not receive herbicide treatment [247]. Cost of Production Budgets for organic cucumber production in California include charges for 30 hours of hand weeding and 3 cultivations [84].

Approximately 60 % of U.S. cucumber acres are treated with herbicides [16]. Without herbicides, cucumber yield is projected to decline by 66% [5].

A.15 Dry Beans

Prior to the use of herbicides, weeds were cultivated from between rows of dry beans, while hand weeders were usually employed to remove weeds growing directly in the bean row [4]. Due to increased scarcity and cost of labor for hand weeding, more than 40 chemicals were evaluated for the control of annual weeds in field bean fields in the 1950s [4].

The most effective chemical studied was EPTC, which provided excellent control of all annual weeds encountered over a three-year period without injuring the bean crop. Broadcast applications of EPTC reduced hand weeding requirements by 16.5 hours/acre, and resulted in 38% higher yields than the hand weeded check [4].

A 1978 survey of growers in the Midwest indicated that herbicides were used on 95% of dry bean acreage, while a 1992 survey indicated that 99% of the dry bean acres in Minnesota and North Dakota were treated with herbicides [3] [172]. It has been estimated that without herbicides, U.S. dry bean yields would decline by 25% [5].

A.16 Grapes

Historically, weed control in California vineyards meant allowing weeds to grow during winter, disking the middles in spring, and plowing vine rows. Weeds in the middles were primarily managed mechanically. The plow used in the rows is referred to as the French plow; it has a trip arm that hydraulically moves the plow around the vine. The advent in the 1960s of pre-emergence residual herbicides, which could be applied down the row during fall or winter, provided clean rows without the need to plow close to the vines [56]. Weeds in the middle of the rows could be managed chemically or with mechanical cultivators.

Growers moved away from the French plow, to the use of herbicides for several reasons: (1) Less labor was required (even with the plow, hand hoeing one time around the vines was usually essential) [56]; (2) Mechanical injury to the vine was eliminated (grapevines were sometimes accidentally torn out by the French plow); and (3) herbicides provided longer lasting weed control and were more effective on annual weeds [57]. Research showed that residual herbicides would provide more than 10 months of control of germinating weed seeds [58]. A comparison of grape yields showed a 5% increase when herbicides replaced the French plow [59]. A recent study estimated that California grape growers could go without herbicides, with no reduction in yield, by substituting one mechanical weeding in the row supplemented with 11 hours of hand weeding per acre [53]. A similar point is made in a Cost of Production Budget for organic grapes, prepared by the University of California, which includes the cost of one cultivation of weeds under the vines and 8 hours per acre for hand weeding under the vines [60]. The Report states that hand weeding requirements in organic vineyards can vary from 6-12 hours per acre [60]. Organic vineyards with high densities of perennial weeds require greater control measures [386].

In New York, grape growers began routine use of residual herbicides for weed control in the 1960s due to research trials demonstrating efficacy and the high labor input previously used [61]. Research demonstrated that the labor involved in chemical weed control was approximately one-third of mechanical and hand hoeing in the row under the trellis [64]. A recent five-year study of the feasibility of organic grape production in New York indicated the need for 8 cultivation operations and 13 hours of hand weeding to replace herbicides [62]. Even with these activities, the yields of the organic grapes were 5 to 35% lower than the conventional vineyards [62]. The lack of effective weed control in the organic vineyards is the primary reason for the lower yields [63]. A recent study estimated that without herbicides, New York grape growers would cultivate and hand weed as replacements and yield would be 12% lower [53].

In 1964, approximately 25% of U.S. grape acreage was treated with herbicides [376]. USDA pesticide-use surveys conducted in the 1990s indicate that approximately two-thirds of California's grape acreage is treated with herbicides, while approximately 90% of Eastern grape acreage is treated [14]. It is estimated that grape yields would not decline in California without herbicides; while in other states, the decline would be 12-35% [5]. Because of California's domination of U.S. grape production, without herbicides, national grape production would decline by 1%.

A.17 Green Beans

Prior to the introduction of herbicides, weed control with hand weeding and cultivation represented one of the most expensive items in green bean production [291]. Weeds reduced the efficiency of mechanical bean pickers, causing yield losses during harvest [148]. In an attempt to reduce weed control costs, research began in the early 1950s with pre-emergence herbicides. In New York during the 1950s, 13 demonstrations resulted in extra yield of 375 pounds per acre in the herbicide treated plots [291]. Recently, a three-year comparative product performance experiment was conducted in New York, which compared herbicide treatments to hand weeded and cultivated plots [292]. Uncontrolled weeds reduced green bean yields by 50%, while 2 cultivations alone resulted in a 33% yield reduction, in comparison to herbicide treatments. The combination of two cultivations and 12 hours of hand weeding per acre produced yields 20% lower than herbicide treatments. Fifty-four hours of hand weeding per acre resulted in green bean yields that were only 7% lower than the herbicide treatments [292]. Processing green beans are frequently grown on large acreages, and excessive rainfall often results in heavy weed pressure and delays timely cultivation [293]. Growers find that the risks associated with relying on cultivation alone are too great. Growers have estimated that yields can be reduced by up to 50% when heavy infestations occur and up to a total loss when weeds prevent mechanical harvesting.

In the early 1990s, green bean growers did not have an effective broadleaf herbicide, due to the cancellation of dinoseb and the withdrawal of the registration for chloramben. Documented dollar losses in New York, due to increased green bean weed pressure in 1992, include the following: decreased harvester efficiency (loss of small beans, increased trucking costs for culls), $249,000; field abandonment due to weeds after planting, $141,000; and load rejection at processors due to nightshade berry contamination, $10,000 [294]. An organic green bean grower in Vermont reports the need for 17.5 hours of hand weeding per acre following 6 cultivations [299]. Approximately 96 % of U.S. processed green bean acreage is treated with herbicides

[16]. Nationally, without herbicides, it is estimated that green bean yield would decline by 20% [5].

A.18 Green Peas

Weed control in processing peas is more important than in many other crops since weed competition not only reduces yields of shelled peas, but weeds also contaminate harvested peas with seeds or fragments that reduce the quality and market value of the peas [281]. Canada thistle buds and nightshade berries are similar in size and shape to peas and are difficult to remove from harvested peas. Growers can have pea loads docked or entire fields left unharvested due to Canada thistle contamination. Removing nightshade is particularly important because the berries are poisonous [282]. It is essential to keep pea fields relatively weed-free, ensuring high quality green peas [282].

Weeds reduce the yields and the quality of peas when moisture is limiting. Weed competition under these conditions causes the typically tender, high-quality peas to become hard. These small, hard peas are difficult to separate. Therefore, they reduce the grade of the processed product. In the 1950s, it was estimated that weeds lowered U.S. green pea production by 13%, which included a 3% loss due to lower quality [148]. Since growers plant green peas in narrow rows, it is difficult to use cultivators without severely injuring the peas [282]. Prior to the development of herbicides, growers frequently found it necessary to go through pea fields with a scythe and cut the thistle plants [283]. Early experiments with herbicides showed a reduction of 90% in Canada thistle development in treated pea fields [283]. Herbicide use in peas expanded rapidly due to excellent control of Canada thistle, nightshades and annual broadleaf and grassy weeds, which had been reducing yields by up to 64% in some fields [284].

Weeds are a major problem in organic pea production [285]. Research has shown that 12 hours of hand weeding is one option for organic pea growers [285]. Another option that has been researched is to increase row spacing of peas to 18-24 inches, so that cultivation becomes possible. However, pea yields are 26-31% lower with the increased row spacing [285].

Approximately 94% of U.S. processed green pea acreage is treated with herbicides [16]. Nationally, without herbicides, it is estimated that green pea yield would decline by 20% [5].

A.19 Hops

Dried hop cones are used as flavor components in the brewing of beers and ales. Once established, the hop rootstock will produce indefinitely, although industry practice is to rotate plantings every 10 years [216].

Herbicides are used on 100% of the hop acreage in the U.S. Herbicides are important to the industry for desiccation of hop suckers and excess foliage, as well as for control of various annual and perennial grasses and broadleaf weeds [216]. Tillage has been the primary means of weed control in hop yards. In rill-irrigated hop yards, cultivation occurs four to six times during the season to keep weeds under control. Substantial acreage has been converted to drip irrigation during the past decade, due largely to water quality-related regulatory pressures. This has resulted in growers moving away from the standard 7’x7’ hill spacing (which allowed for cross-cultivation) to 3.5’x14’ spacing (which required half as much drip tubing, but eliminates the ability to cross-cultivate). In the spring, desiccants are utilized to remove early growth prior to training. After training, herbicides are used at the base of the hop plants to remove weeds, as well as to burn back basal sucker growth and lower leaves of the hop plant.

The lower leaves need to be removed from hop vines in order to improve airflow through the hop yard, and to control diseases such as powdery mildew and insect pests that spread from the lower growth up into the top growth. Prior to the development of chemical herbicides/desiccants, the lower leaves were removed by hand. Hand stripping was not always effective, since stripping wounds served as points of entry for diseases and often weakened the vines so that they cracked or broke off in midseason [217]. Approximately 20-50 hours of hand labor was required to manually defoliate the lower parts of the hop plants [238]. Research with herbicides indicated that they could be used to provide effective weed control at the base of the hop plants, as well as provide effective hop sucker control [239].

Prior to 1997, powdery mildew had not been observed in the Pacific Northwest. Since 1997, the disease has become established in the hop-growing region in the Northwest. Highly susceptible varieties experience 100% yield loss without control. Mildew infested hops are not marketable [216]. Control of hop powdery mildew relies on application of desiccant herbicides combined with application of protectant fungicides. The basal growth of suckers results in thick mats of vegetation that are not penetrated by fungicides, and create ideal environmental conditions for development of powdery mildew. The only effective way for managing this source of inoculum is to remove the tissue. Research has shown that herbicide desiccants reduce the incidence of powdery mildew by 25% [248].

A.20 Hot Peppers

New Mexico is the leading producer of chile peppers in the U.S. Chile peppers are direct seeded in March, germinate in three to four weeks and are thinned by hand. Chiles grow slowly at the beginning of the season, giving rapidly growing weeds a competitive advantage. Uncontrolled weeds have been documented to reduce chile yields by up to 76% [362].

Chiles are harvested by hand, and workers will not enter weed-infested fields because weeds decrease their picking speed, and therefore their wage, since they are paid for the amount they pick, not for their time [363]. Mechanical cultivation can effectively control weeds only between the rows. Weeds in the rows can significantly reduce chile yields. Research has shown that chile yields are reduced 33% when only cultivation is used for weed control [364]. A combination of trifluralin and s-metolachlor is widely used to control a broad spectrum of weeds in chiles. A two-year research study demonstrated that chile yields could be equivalent between fields treated with trifluralin/s-metolachlor and fields that were hand weeded [365]. However, an extra 42-79 hours of hand weeding was required.

Chile acreage peaked during 1992 in New Mexico and has then declined, due to increased competition and imports from Mexico, where labor costs are significantly lower (See Figure A12). Many growers cited problems obtaining labor as a reason for abandoning chile production in New Mexico [367]. A research program has been established to determine ways of reducing the amount of labor required in chile production, including the development of mechanical harvesters [366].

A.21 Lettuce

Prior to the development of effective herbicides, severe weed infestations sometimes caused complete lettuce crop losses in California [71]. Up through the early 1960s, lettuce growers used hand weeding, with short-handled hoes, and cultivation for weed control. With increasing labor costs and the increasing scarcity of labor, more emphasis was put on chemical weed control through residual pre-emergence herbicides [73]. Research demonstrated that the use of pre-emergence herbicides could reduce hand weeding time by 55% [18]. A drawback of hand hoeing lettuce is that lettuce plants are sometimes removed along with weeds. The loss of one lettuce plant per six foot of row results in the loss of 181 cartons of lettuce per acre at harvest [75]. Lettuce is often grown in rotation with crops that have previously been fumigated for weed control. Organic lettuce growers in California typically cultivate three times and use 18 hours of hand weeding per acre [84].

Approximately 50% of California lettuce acreage is treated with herbicides [16]. Recent estimates show that without the use of herbicides, California lettuce growers would double their use of cultivation (two additional cultivations) and increase hand weeding by 38 hours per acre [53]. Even with this increase, lettuce yields are predicted to decline by 13% if herbicides are not used [53].

In Florida, lettuce is grown in mineral soils. Mineral soils have a unique soil texture that eliminates mechanical cultivation as a viable alternative, since this technique disrupts the necessary bed configuration on which the crop is growing. Very few herbicides have proved efficacious for controlling weeds in the mineral soils of the Florida Everglades region. Herbicides such as benefin, pronamide and bensulide, used by lettuce growers in other states, are not recommended for use in Florida mineral soils because they are inactivated by the high soil organic matter [76]. These herbicides degrade rapidly in the mineral soils because of the high soil microbial activity and high temperatures [77]. The herbicide CDEC (trade name Vegadex) proved to be effective for pre-emergence weed control in lettuce and was recommended for commercial plantings on organic soils in Florida [78]. In 1982, the manufacturer of CDEC ceased production of the herbicide. The existing stocks of the herbicide were used up by the middle 1980s. EPA canceled its registration in 1984.

Beginning in 1985, Florida lettuce growers no longer had an herbicide available for weed control within the row of lettuce plants. Between 1985-1990, lettuce growers increased the use of hand labor for controlling weeds to approximately $200/A [79]. Because of the increased expense and difficulty of finding labor, several growers withdrew land from lettuce production [80]. Approximately 5,000 acres were withdrawn from lettuce production, reducing lettuce production annually by about 85 million pounds, valued at about $13 million (see Figure A13).

Prior to the mid-1980s, pigweed was not present in economic populations in the Everglades region due to the use of CDEC. Hand hoeing alone cannot control pigweed completely. As a result, pigweed infestations steadily increased and expanded in the late 1980s and early 1990s, leading to an increase in the amount of hand labor to approximately $750/A in 1993 [80]. In the winter of 1992-1993, a crisis situation occurred because of abnormal weather conditions; high rainfall and temperatures prevented timely hand weeding, and pigweeds took over certain fields completely.

Approximately $900,000 in lost lettuce production occurred that year because of failure to control pigweed [80].

Further losses were prevented by the issuance of an emergency exemption for use of the herbicide imazethapyr to control emerged pigweeds in February 1993. Subsequently, imazethapyr (trade name Pursuit) received a full label for use in Florida lettuce fields. Research had demonstrated that imazethapyr would control broadleaf weeds (including pigweed) on the highly organic soils of the Everglades muck lettuce-growing region [77]. Since 1993, imazethapyr has substituted for the hand weeding at a cost of $20/A.

An organic lettuce grower in Maine reports the need for six hours of hand weeding per acre following two cultivations [299]. Research in New Jersey indicated that lettuce yields were equivalent when 224-424 hours of hand weeding and two to three cultivations substituted for herbicides [83]. Approximately 95% of New Jersey's lettuce acreage is treated with herbicides, and the likely yield loss without herbicides is projected at 50% [5].

A.22 Mint

Approximately 11 million pounds of mint oil were produced in 2001 from 110,000 acres of mint grown in the U.S. This acreage is comprised of both peppermint and spearmint. About 90% of the mint oil produced annually is used in by the chewing gum and oral care industries. One of the major properties of mint oil used as a flavoring ingredient is its strength of taste and aroma. One pound (pint) of mint oil can flavor 40,000 sticks of chewing gum or between 1,000 and 1,500 tubes of toothpaste. Mint oil yield is considerably reduced when weeds compete with the mint plant for light, nutrients and soil moisture. Mint oil quality is also reduced when weeds impart off-flavors and odors to the mint oil during the distillation process [408]. Research has demonstrated that mint yields can be reduced by up to 80% from uncontrolled Canada thistle infestations while a pure stand of quackgrass can result in a complete loss of mint oil yield [408]. Combinations of annual broadleaf and grassy weeds can commonly cause mint oil yield reductions of 26-66% [408]. Infestations of horseweed, pigweed, western goldenrod, common lambsquarters and prickly lettuce (at 7 or more plants per square yard) can make mint oil unmarketable [408]. In the early 1950s fall or spring cultivation of plowing and harrowing mint fields was the most common type weed control practiced in mint [409]. Geese and/or sheep were also often brought into the fields once the plants were too large to cultivate. The animals usually preferred weeds to the mint plant. The animals were not entirely satisfactory for weeding since they ate only certain weeds and were troublesome to manage [410]. In the 1950s a fungal pathogen named verticillium wilt was widespread in U.S. mint fields and cultivation was reduced since the cultivation spread verticillium wilt. Hand weeding that typically required 4 weedings throughout the growing season then became more important in mint fields. Hand weeding crews often physically damaged the mint stands and in so doing reduced yields [408]. With the advent of new herbicides mint growers began using Sinbar (terbacil) for broad-spectrum selective weed control in the late 1960s. Research showed that using herbicides such as Sinbar in mint reduced hand weeding by 18-24 hours per acre [116]. Mint growers also significantly expanded acreage into fields that had been avoided previously due to problem weed infestations [116]. Research has estimated that the use of at least 48 hours per acre of careful hand hoeing for weeds could result in mint oil yield and quality equivalent to herbicide treatment [127]. Today this amount of labor is both unavailable and unaffordable for mint growers. Without herbicides the yield of mint would be reduced by an average of 35% with a marketable value of 65% of mint oil uncontaminated by weeds [192].

A.23 Onions

For several reasons, weed control in onions relies heavily on herbicides. The slow germination of the onion from the seed and the slow growth of small onions, allow weeds to get a head start on the crop. Onions do not compete well against weeds. Onions have narrow, upright leaves that do not shade the ground to inhibit competitors [81].

Pre-emergence herbicides give the onions a chance early in the season against much quicker growing and competitive weeds [81]. Research has shown that there is no marketable yield of onions if weeds are not controlled [82]. Initial research with herbicides demonstrated that hand weeding labor, with short-handled hoes, was reduced by 120 hours per acre [82]. The pre-emergence herbicides controlled weeds for seven to ten weeks [82]. Because of the widespread use of hand weeding, which was very effective, onion yields did not dramatically increase following the introduction of herbicides for weed control (see Figure A14). Recent research in New Jersey has shown that carefully hand weeded onion plots produced yield equal to the herbicide plots when 1067 hours of labor were used [83].

In California, cost of production budgets for organic onion production includes the following weed control practices: six cultivations, one flaming and 73 hours for hand weeding [84]. Each of the non-chemical practices has the potential of lowering onion yields by damaging to the crop [81] [85]. A recent study estimated that without the use of herbicides, California farmers would not be able to keep up with the increased weed population, despite cultivating two more times and hand weeding seven more times (64 hours/acre) [53]. In addition, hand weeding often disturbs the bulbs and disrupts or even curtails plant growth. Thus, increased hand weeding would have direct negative effects on onion yield [53].

Approximately 88% of U.S. onion acreage is treated with herbicides [16]. Onion yields in California are projected to decline by 35% without herbicides [53]. In Texas, onion yields are projected to decline by 25% without herbicides, despite one more cultivation and 32 more hours of hand weeding [53]. Nationally, onion yields have been projected to decline by 43% without herbicides [5].

A.24 Peaches

Until the 1960s, bare ground culture, maintained by cross-disking until midsummer, was the predominant weed control system in Southeast peach orchards. In the 1960s, growers began to realize that herbicides could be used to reduce the need for disking. By utilizing herbicides, the need to maintain wide row spacing of trees to accommodate cross cultivation was reduced, and growers were able to plant a higher density of trees per acre. It was also determined that cultivation is detrimental to tree growth due to root pruning, and it contributed to soil erosion in peach orchards located on slopes. As a way of reducing the incidence of peach tree short life (PTSL), many growers adopted the use of herbicides in peach orchards. Research demonstrated that a 19% peach tree mortality rate occurred in four years of disc weed control, while the chemical weed control system resulted in no loss [218]. Pythium root rot was much more prevalent in orchards where roots had been damaged by disking. Research demonstrated that the total number of peach tree roots in the top 20 cm of soil surface was 435 higher in the herbicide treated plots, in comparison to the mechanically cultivated plots [219].

After two years, peach tree diameters were 27% greater in plots treated with herbicides, in comparison to trees in cultivated plots [235]. Peach yield in the herbicide plots was 167% higher than in the cultivation plots [235]. Although the cultivated plots were tilled seven times during the season, there was rapid regeneration of weeds after each tillage operation to the extent that weeds were mostly present [235]. In addition, the residual herbicides provided season-long control of most broadleaf and grass weed species [211]. The most common weed control system in Southeastern peach orchards is to use herbicides in a strip down the tree row and to maintain a weed sod between the rows. Control of winter annual weeds is recommended in the Southeast as a means of reducing plant bug damage to peaches.

In 1964, it was estimated that 10% of U.S. peach acreage was treated with herbicides [376].

Recent (1990s) USDA surveys indicate that approximately 75% of U.S. peach acres are treated with herbicides [14]. While 50% of California's peach acres are treated, close to 95% of Georgia's peach acres are treated with herbicides [14].

A recent estimate of the impact of eliminating herbicide use in peach orchards in Georgia/South Carolina shows that peach yields would decline by 20% without herbicides [53]. This estimate assumed that growers would substitute five hours of hand weeding labor for herbicides. In California, it was estimated that peach yields would decline by 1% without herbicides, as growers substituted seven hours of hand weeding [53]. Nationally, it is estimated that peach yields would decline by 11% without herbicides [5].

A.25 Peanuts

Before the 1960s, weeds in peanut fields were usually controlled mechanically and with hand weeding. Cultivation began soon after the plants emerged, and any weeds that escaped were removed with hoes. However, as the farm labor supply dwindled, mechanical weed control became less feasible, especially when wet weather delayed cultivation and stimulated the germination of weed seeds [86]. Peanuts can only be cultivated early in the growing season because of a sprawling growth habit [87]. Two cultivations are estimated to provide 60% control of the weed species infesting peanut fields [96]. Cultivation directly lowers peanut yield, as a result of soil being thrown on the peanut plant, covering lower nodes, thus inhibiting peanut growth [88].

In addition to the inhibition of normal flower and peg development, movement of soil around the fruiting branches of peanuts creates conditions favorable for stem rot diseases. Southern stem rot or “white mold” losses are particularly aggravated by vine damage resulting from cultivation or movement of soil around the crown of the plant [88]. In the 1940s and 1950s, peanut yields were frequently drastically reduced by stem rots [89].

The difficulties in proper mechanical cultivation of peanuts contributed to research into use of herbicides [90]. Research demonstrated that herbicide use increased peanut yield by 47% in comparison with two cultivations, and by 18% in comparison to two cultivations plus hand hoeing [91]. Labor savings of 14 hours per acre were recorded in Georgia [89].

Figure A15 charts herbicide use on U.S. peanut acreage over time. The use of herbicides is cited as a primary factor in the doubling of peanut yields [92] (see Figure A16). Herbicides contributed to increased peanut yields directly, through better control of weeds and, indirectly, through disease prevention [90]. A Georgia peanut grower reported that without herbicides, his peanut yields would decline 50-67%, even with five additional cultivations and an additional five hoeings [354]. A research program in North Carolina for peanuts determined weed control to be the most difficult area to reduce pesticide use [93]. The primary alternative is identified as tillage, which is limited to early in the season and can increase soil-borne diseases [93].

Recent research with organic methods of pest control in peanuts determined that the largest increase in production cost in the organic system was for weed control, which included two cultivations and hand weeding costs of $296-991/A (50-165 hours) [94]. Organic peanut growers report their biggest problem is controlling weeds [298].

Approximately 97% of U.S. peanut acreage is treated with herbicides. A recent economic analysis of pesticide use estimated that without herbicides, U.S. peanut yields would decline by 29%, even with an additional two cultivations and 10 hours of hand weeding per acre [95]. Nationally, it is estimated that peanut yields would decline by 52% without herbicides [5].

A.26 Potatoes

Prior to the introduction of chemical weed killers, U.S. potato growers relied primarily on the use of frequent cultivation for removing weeds. Potato acreage was typically cultivated four to eight times for weed control [107]. Six summer tillage operations were the most common practice [108]. Numerous studies have reported on the negative effects of cultivation on potato yields. Cultivation injures potato roots. One study demonstrated reduced potato yields of 3-21% for consecutive years due to root pruning [109]. Cultivator traffic through potato fields tends to compact the soil. Potato is not a deep-rooting plant and root penetration is impeded when soil is compacted. In a three-year study, soils that were cultivated once had an average weight of 95 pounds per cubic foot, whereas those cultivated five to seven times weighed 98 pounds. One hundred thirty thousand extra pounds of soil were packed into the surface foot of each acre [107]. Between five to seven cultivations reduced the soil air space by 15%. Cultivation has been shown to cause reduced soil moisture and an increased incidence of disease, which lower potato yields [110] [111]. Cultivation also has limited effectiveness in controlling weeds in potato fields because weeds growing in the row of potatoes are missed, and weeds that germinate after potato row closure cannot be controlled by cultivation [112]. Research has shown that growers who followed normal cultivation practices lost 12-20% of total yield production with only two cultivations [112]. Weeds that emerged after the last cultivation interfered with mechanical harvests. Losses of more than 20% were observed in the 1950s [148].

Early research with herbicides in potatoes demonstrated that post-plant tillage could be reduced to one to two trips when residual herbicides were applied early in the season [113]. The herbicide made cultivation unnecessary for four to five weeks [107]. When weeds were controlled with an effective herbicide, there was no yield advantage to three cultivations rather than one cultivation [114]. Research has shown that the use of a residual herbicide along with one tillage operation produced potato yields 29% greater than with three cultivations [115].

Prior to the introduction of herbicides, a sizeable proportion of Long Island's potatoes were rendered unmarketable because of nut sedge shoots growing through them. Grade losses of up to 25% were observed in the 1950s [148]. Increased use of herbicides is credited with reducing tillage in potato fields with the average acre cultivated twice [152] and is credited as a factor in increased potato yields due to more effective, less damaging weed management [66].

An experiment with organic potato production in Wisconsin resulted in a yield reduction of 36% [303]. An Oregon organic potato grower reported that organic yields are generally 25% below neighboring conventional potato fields [308].

Approximately 93 % of U.S. potato acreage is treated with herbicides. Figure A17 charts herbicide use on U.S. potato acreage over time. A recent study has estimated that without herbicides, U.S. potato growers would make five to six additional tillage trips and use eight to twelve hours of hand weeding labor per acre [53]. Potato yields were estimated to be reduced 25-30%, despite the additional tillage and hand weeding. Nationally, it is estimated that potato yields would decline by 32% without herbicides [5].

A. 27 Raspberries

Prior to the introduction of herbicides, raspberry growers used cultivation and hand weeding to remove weeds. The typical grower from the 1920s to 1950s made nine cultivation trips for weed control purposes [23]. Forty-three hours per acre were required for cultivating and hand weeding [24].

Research with residual herbicides in the late 1950s demonstrated that control of essentially 100% of troublesome weed species could be achieved with a single application [25]. Currently, raspberry growers do not have to cultivate or hand weed since herbicides are used [26]. The adoption of chemical sprays for weed control is credited in causing the greatest reduction in production costs for raspberries [27]. In 1964, it was estimated that 25% of U.S. raspberry acreage was treated with herbicides [376].

USDA surveys of growers in the Northwest indicated that 89-92% of the raspberry acreage was typically treated with herbicides throughout the 1990s [14]. Organic raspberry growers typically utilize cultivation and hand weeding for weed control purposes [28].

A.28 Rice

In the U.S., rice is direct-seeded. However, the vast majority of the world's rice area, principally in Asia, is still transplanted. Most rice historians believe that the ancient practice of transplanting was adopted primarily to control weeds [130]. Three to five-week-old transplant seedlings have a head start on newly germinating weeds, as well as the advantage of tolerating a continuous flood that further suppresses weed growth. In the U.S., transplanting rice is labor-intensive and too expensive a practice to be practical. In California, rice was initially dry-seeded, but the rapid buildup of barnyardgrass rendered much of the land useless for rice production after three years [131]. A system of water-seeding rice in continuously flooded fields began in the 1920s as a method to control severe barnyardgrass infestations. The water-seeding method is credited with saving the California rice industry. Water-seeding of rice in Southern states followed its development in California. One of the main reasons for adoption was to control grassy weeds [132]. The change to water-seeded rice encouraged the development of other weed problems, including broadleaf aquatic species and, in California, the Eurasian variety of barnyardgrass known as "water grass." The larger seeds of the Asian grasses enable them to germinate and emerge through deep water. Although hand weeding is the main method of weed control in Asian rice fields, where rice is grown in rows, hand weeding is not used in the U.S. Cultivation of rice after crop emergence is impossible in dry broadcast and water-seeded rice [133].

The first herbicides used in U.S. rice production were 2,4-D, 2,4-5T, and MCPA, which provided control of broadleaf weeds and sedges. The herbicides propanil and molinate were introduced in the 1960s, providing effective control of grassy weeds in rice. Research demonstrated that rice yields increased by 60% in plots treated with propanil [134]. In California, research demonstrated a 160% increase in rice yields when molinate was applied for water grass control [135]. Beginning in the 1960s until the early 1970s, the use of propanil and molinate for the control of weed grasses in rice steadily increased. During this period, per acre rice yields in the U.S. increased by 35% (See Figure A18). Better weed control with the herbicides is credited as an important factor in the increased yield [133].

In the 1970s, new high-yielding, short-statured (semi-dwarf) rice cultivars were introduced. These varieties were practical for U.S. growers only because of effective weed control with herbicides [133]. The semi-dwarf varieties are less able to survive in deep water and flood levels have been reduced [136]. Semi-dwarf varieties are more erect in growth and provide less shading, which stimulates weed growth [133] [137]. Planting of the semi-dwarf varieties led to another 35% increase in U.S. rice yields [137].

Organic rice growers report that weed management is the most difficult part of organic production, and it is the major reason that organic rice yields are 50% lower than conventional yields [138]. The University of California has prepared cost of production budgets for organic and conventional rice, which indicate a 38% reduction in rice yield in the organic system [139] [140]. One prominent California organic rice grower leaves the fields in fallow for a year and cultivates three times to reduce the weed population [387].

Approximately 98% of U.S. rice acres are treated with herbicides. Figure A19 charts herbicide use on U.S. rice acreage over time. A recent report estimated that without herbicide usage, U.S. rice yields would decline by 53% [95].

A.29 Sorghum

Livestock and poultry feeding account for about 98% of total U.S. sorghum use. Sorghum accounts for 6 to 8 percent of all concentrates fed to livestock and poultry. For beef cattle, sorghum’s share rises to 18 to 22 percent, primarily because a large fed beef industry has developed in the sorghum belt. Sorghum production is centered in the Central and Southern Plains. Sorghum is popular in this area because it resists drought better than crops such as wheat or corn (sorghum requires less water). Sorghum is unique, in that it can remain dormant during stress periods and renew growth when conditions are more favorable. Sorghum yields increased dramatically beginning in the 1960s.

In the 1960s, the introduction of residual pre-emergence herbicides (atrazine and propazine) contributed to the yield increase; other factors included new hybrids, fertilization, and irrigation [65] [66]. Sorghum seedlings are small and weak, grow slowly, and do not compete with weeds. Prior to the use of herbicides, weeds were removed from sorghum fields with mechanical cultivation. Common practice was to cultivate out several flushes of weeds prior to planting sorghum, and to follow up with several cultivations during the growing season [67].

Cultivation resulted in lower sorghum yields for several reasons. The mechanical operations ahead of planting loosened the top few inches of soil, so that moisture was lost from the soil surface. Repeated tillage destroyed wheat stubble residue, leaving the soil surface bare and subject to crusting and erosion [68]. Weeds that emerged during the season prior to cultivation consumed moisture, and cultivation could not be used to remove weeds in the sorghum rows [69].

Research demonstrated that pre-emergence applications of propazine and atrazine resulted in yields 34% higher than sorghum that was cultivated three times [70]. By controlling weeds prior to planting, the herbicides allowed sorghum to be planted earlier, with no need to wait for weed flushes. As a result, growers could plant longer season (higher yielding) hybrids [66].

USDA surveys indicate that herbicide use on U.S. sorghum acreage increased from 14% of the acres treated in 1959 to 59% of the acres treated in 1982 [168]-[170] [173]. The latest USDA surveys of sorghum indicated that 78% of the acres were treated in 1991, while 91% were treated in 1998 [117]. Recent estimates of the impact of not using herbicides in sorghum show that yields would decline by 20–30 % in the central and Southern Plains states [5].

A.30 Soybeans

Soybeans were grown primarily as forage crops in the U.S. through the 1930s. Prior to World War II, the U.S. imported 40% of its edible fats and oils. At the advent of the War, this supply was cut, and processors turned to domestically produced soybean oil [141]. World demand for cooking oil, salad oil and red meat increased substantially immediately after World War II. These demands stimulated the rapid expansion of soybean production in the U.S. [142]. In the 1950s, soybean meal became available as a low-cost, high-protein feed ingredient, triggering explosive growth in U.S. livestock and poultry production.

In the 1940s and 1950s, tillage was the primary method used to control weeds in U.S. soybeans. The use of several cultivations prior to planting soybeans was regularly recommended. Various implements were used after planting to perform shallow tillage, which uproots very young annual weeds between the soybean rows. Research demonstrated that rotary hoeing provided 70-80% weed control three to five days after soybean emergence, with two repeat treatments at five-day intervals [143]. However, untimely rotary hoeing applied while weed seedlings were bigger (in the one to three leaf stage) decreased weed control effectiveness to 50% [143]. Timely weed removal treatments with the rotary hoe were sometimes difficult to apply due to wet conditions, i.e., mud balls up excessively on the rotary hoe. Prolonged rainy periods often delayed the use of the rotary hoe in farmers' fields, beyond the time when hoeing is effective. If rotary hoeing is delayed, the weeds develop extensive root systems, preventing their removal with the implement [144]. The best weed removal system for soybeans in the 1950s was determined to be two timely rotary hoeings, along with two shovel cultivations [145]. Even with timely usage of cultivation, soybean yields were reduced because the tillage operations did not effectively control the weeds growing in the row alongside the soybeans. An 11-year experiment (1952-1962) in Iowa estimated soybean yield reductions resulting from weed infestations that were able to survive good cultural and mechanical weed control methods [146]. Average soybean yield reduction was 10%, despite the best mechanical weed control practices that confined weeds to a four to six inch band centered on the soybean row. In the 1950s and 1960s, soybean growers generally cultivated two to three times [144] [147]. USDA estimated that the average annual national loss in the potential production of soybeans, due to weeds, was 17% for the period between 1951 and 1960. The USDA loss estimate includes a yield loss of 14%

and a loss of 3 percent in quality, due to weed seed dockage, damage in cleaning to remove weed seeds, split beans due to presence of weed seeds and off-flavors [148].

U.S. soybean growers began to use herbicides for weed control in the late 1950s. By 1982, more than 90% of the national acreage was treated (see Figure A20). Research demonstrated that combinations of herbicides could provide more than 90% control of all major weeds that infest soybeans [149][150].

By the early 1990s, there were at least 70 registrations for individual herbicides or packaged herbicide mixtures for weed management in soybeans. As a result, most weeds in soybeans could be adequately controlled with herbicides [151]. In 1992, U.S. soybean losses due to weeds were estimated at 7% [5]. Increased use of herbicides led to significant reductions in the number of cultivations of U.S. soybean acreage. In 1994, only 43% of U.S. soybean acreage received any cultivation that averaged one time during the season [152]. Between 1965 and 1985, average U.S. soybean yields increased by 40% (see Figure A21). A statistical analysis of the increase in soybean yield from 1965 to 1979 concluded that weed control provided by the use of herbicides accounted for 62% of the yield increase [153].

An organic soybean grower in South Dakota reports that yields can be 15% lower [298]. This grower has 350 acres of organic soybeans and reports that after three tillage operations, soybean rows are walked by children every morning with machetes and knives to cut emerged weeds [298]. Another South Dakota organic soybean farmer reported that organic yields were 30-40% lower than conventional yields even with three to four times the tillage [43]. An organic soybean grower highlighted the problem of being unable to cultivate and rotary hoe following a wet spring. The organic grower had to spend $140/A for hand weeding crews in comparison to $25/A, which was typical in dry years [40]. A University of Illinois guide for producing organic food-grade soybeans indicated a need for six tillage trips for weed control [304]. A Michigan State University Production Budget for organic soybeans includes a charge for five hours of labor for weeding [310]. An Illinois organic soybean grower with 500 acres in three fields reported that one field was hand weeded by children, but due to a lack of time, the other two fields were not weeded [318]. Approximately 96 % of U.S. soybean acreage is treated with herbicides [117]. Nationally, it is estimated that soybean yields would decline by 26% without herbicides [5].

A.31 Spinach

Prior to the introduction of herbicides, weeds were controlled to some extent in spinach with hand hoeing and cultivation. Hand weeding caused severe yield losses due to incidental removal of crop plants with the weeds. Yield losses of one-third were observed in the 1950s [148]. Many weeds remained in the spinach row after cultivating and hoeing [287]. Since processing spinach is mechanically harvested with mowers, any weeds present are cut along with the spinach and sent to the processor. Prior to the introduction of herbicides, weeds in spinach became one of the most common complaints that food processors received from customers [286]. It was common practice that fields, or parts of fields, were not harvested because of the presence of weeds in spinach [288]. Heavy weed infestations reduced spinach yields by 50%. In the 1950s, it was estimated that the value of U.S. spinach was lowered by 13% due to weed contamination [148].

Research with herbicides in spinach showed that the weight of weeds per acre could be reduced significantly, by up to 900 pounds per acre [289]. Spinach yields increased following the introduction of herbicides because the spacing between rows was reduced since cultivation was no longer necessary [290]. Research in New Jersey has shown that 209 hours of hand weeding per acre is required to produce spinach yields equivalent to herbicide-treated acreage [83]. Approximately 90% of U.S. processed spinach receives annual herbicide treatments [16].

In 1989, New Jersey growers had exhausted supplies of the herbicide chlorpropham, which had been cancelled for use on spinach. Without an effective alternative for post-emergence control of chickweed, many fields were disked instead of harvested [257]. Spinach production in the state was reduced by 17% (see Figure A22).

A.32 Strawberries

Strawberry plants are shallow-rooted and compete poorly against weeds for sunlight, nutrients and moisture. Only occasional mechanical cultivation is practical during the growing season, due to frequent irrigations and large quantities of fruit hanging on the row [261]. In the 1950s and early 1960s, hand weeding was the only option for strawberry growers to use and, as a result, weed control was one of the most expensive operations in strawberry operations. Hand weeding costs of $200-$400 per acre were common in California [261]. In Florida, hand weeding was necessary two to four times during the season, with a total requirement of 16 to 40 hours of labor [262]. Two strawberry production systems developed in the late 1960s.

In California and Florida, strawberries are grown as annuals. Before planting, strawberry fields are fumigated with methyl bromide and then covered with plastic. Methyl bromide kills nematodes, insects, disease pathogens and germinating weed seeds. Herbicides are used in conjunction with fumigation: (1) to control weeds with hard seed coats that are not controlled by fumigation; (2) to control weeds that germinate and emerge after the effects of fumigation have dissipated - these weeds can appear from the holes in the plastic around the strawberry plant; and (3) to control weeds in the furrows between the strawberry beds. Hand weeding could be used instead of herbicides in the fumigated fields; however, additional costs of $800 to $2,000 per acre would be incurred if herbicides were not available [263]. Research has shown that equivalent strawberry yields can be obtained with the use of 142 hours of hand weeding per acre instead of fumigation and the use of herbicides [266].

In California, strawberry yields from organic fields are reported to range from 25 to 60% of the conventional yields [264]. Organic growers confirm these lower yields and report that the labor costs for hand weeding are one of the most significant costs for organic production [265].

In other strawberry producing states such as Oregon, Pennsylvania, Michigan and North Carolina, strawberries are grown as a perennial crop, often producing for three to four years. Immediately after planting, residual herbicides are applied as pre-emergent weed control [267]. Additional residual and systemic herbicides are used to reduce emerging weeds throughout the growing season. Winters in several of these states (such as Oregon) are mild-rainy and relatively warm. Such conditions allow weeds to grow throughout the winter. Hand weeding and tillage cannot be performed in a timely fashion during the rainy winter, and growers use residual herbicides to prevent the winter weed growth. Yield losses are estimated at 60 % without control [268]. Early research with residual herbicides in the perennial system demonstrated that hand weeding could be reduced 75 to 85% [269].

A recent USDA study estimated that without the use of herbicides, many of the states with perennial strawberry plantings would experience significant acreage reductions, due to the high cost of hand weeding as a replacement [270]. Overall, USDA estimated that U.S. strawberry production would decline by 30% without the use of herbicides [270].

A.33 Sugarbeets

Hand weeding of sugarbeet fields was standard practice from the 1700s, when German scientists first discovered that the sugarbeet contained commercial quantities of sugar, until the 1950s, when selective herbicides were introduced [185]. Typically, two hoeing operations were made in-season, totaling 11 hours per acre [186]. Workers used long-handled hoes in these operations. In addition, approximately 20 hours of labor per acre were required to thin and weed sugarbeet stands early in the season [186]. The workers would go down the row, usually on their knees, with a short-handled hoe [186].

The introduction of chemical herbicides, which prevented the emergence of weeds in the row of sugarbeet plants, made it possible to reduce the hours of labor used in the weeding/thinning operation, as well as in the subsequent hand weeding operations. Research demonstrated that applications of cycloate and phenmedipham provided effective control of broadleaf and grassy weeds, reducing the need for labor by 90% [189]. Mechanical thinning and herbicide use were rapidly adopted on U.S. sugarbeet acreage, due to the impact on reducing the need for labor. Prior to the development of herbicides, sugarbeet growers often faced years in which the labor for control of weeds was in short supply and difficult to obtain [190]. The development of herbicides was seen as an absolute necessity if the sugarbeet industry was to survive, due to the high labor requirements for sugarbeets in comparison to other crops and the declining availability of labor [191].

Approximately 98% of U.S. sugarbeet acreage is treated with herbicides annually [117]. Figure A23 charts herbicide use in the U.S. on sugarbeets, over time. Nationally, it is estimated that sugarbeet yields would decline by 29% without herbicides [5].

A.34 Sugarcane

Prior to 1940, a great deal of labor was available in the sugarcane area of Louisiana. Johnsongrass and all other weeds were held in check by continuous hoeing and digging [99]. Approximately 40 to 70 hours of hand labor were required to weed an acre of sugarcane [102]. Impacts of the war years resulted in a shortage of labor for hand weeding with a resultant buildup of johnsongrass infestations. In 1949, at least one-third of the sugarcane acreage of Louisiana was so thoroughly infested that the yield of cane was materially reduced, and one-sixth of the acreage was so badly infested with johnsongrass that sugarcane production was marginal [100]. Reported sugarcane yield losses to johnsongrass were 23-50% [103]. It was thought that some fields were so infested, the only recourse was to replace sugarcane with pasture [101]. More than 200 chemicals were initially evaluated for weed control in sugarcane [104].

As herbicide programs were put into practice to control johnsongrass, it was found that nearly all the other grasses and broad leaf weeds were also being eliminated [101]. Herbicides replaced hand hoeing, and also led to a reduction in the number of in-season cultivations; from seven to eight times to four to five [105][106]. Herbicide use is one of the factors that led to a significant increase in Louisiana sugarcane yields in the 1950s to 1960s (see Figure A24).

Herbicide use led to increased yields as a result of more effective weed control, which also facilitated higher sugarcane plant populations and increased efficiency of fertilizers [100]. Nationally, it is estimated that sugarcane yields would decline by 25% without herbicides [5].

A.35 Sunflowers

Small acreages of sunflower have been grown in the U.S. since 1900. However, the great expansion of acreage in North Dakota, South Dakota and Minnesota did not take place until the early 1970s. Research in the early 1970s in North Dakota indicated that in a weedy plot, sunflower yields were 53% lower than in a weed-free plot [254].

Since sunflowers normally do not emerge for 10 days to two weeks after planting, shallow tillage with a spike tooth or coil spring harrow can be used about one week after planting to kill many weeds [255]. Because sunflower seedlings are strongly rooted, these implements and others, such as the rotary hoe, also can be used to kill weeds after the sunflowers emerge. One to two pre-plant tillage trips can be followed by three to five harrowings and one to three cultivations during the growing season [256]. Cultivation destroys weeds between sunflower rows, but the weeds remaining in the row reduce yields.

Research demonstrated sunflower yield reductions of 12-20% with cultivation (avg. 16%) [254] [259]. NDSU Extension Service has estimated that organic sunflower yields are 25% lower than conventional yields [260]. Approximately 95% of U.S. sunflower acreage is treated with herbicides [117].

A.36 Sweet Corn

Sweet corn is a poor competitor with weeds, due to a limited root system and poor late season canopy closure [237]. Sweet corn doesn't grow as rapidly or as tall as field corn. Sweet corn lacks a dense plant canopy and allows considerable light to enter for weed development. This late-season weed growth limits the effectiveness of mechanical cultivation in sweet corn. Late germinating weeds reduce sweet corn yields directly and also make mechanical sweet corn harvesting nearly impossible. In years of limited rainfall, weeds that remain in the row sometimes reduced sweet corn yields by as much as 50% in the 1950s [148].

Weeds are regarded as one of the most difficult problems in organic sweet corn [240]. At least three cultivations are required in organic sweet corn in New York [241]. The cost of the cultivation treatments is at least twice the cost of herbicide-treated sweet corn [242]. Some organic growers find it necessary to supplement cultivation with hand weeding crews late in the season [240]. In these cases, the cost of weed control is five times greater in the organic system, in comparison with the herbicide treated sweet corn [240]. Cost of Production Budgets for organic sweet corn includes a charge for three cultivation trips [84]. An organic sweet corn grower reports that two hours of child labor per acre is used for pulling big weeds following five cultivation trips [299].

Wisconsin is a major producer of sweet corn. Wisconsin sweet corn acreage and volume of production have declined about 45% since 1990 (see Figure A25). One of the major reasons for this decline is the state's groundwater protection regulations, which either prohibit or limit the use of the herbicide atrazine, depending on the location [243]. This prohibition makes weed control more expensive and sometimes impossible to attain. In addition, availability of sweet corn raw product becomes less dependable for processors. Thus, many food-processing companies have closed or moved sweet corn acreage to other states, where atrazine can still be used at effective rates [243].

A recent report estimated that without herbicides, sweet corn growers would increase cultivation by two to three trips [53]. Cultivation is viewed as less effective, with a risk of crop failure in a very rainy year [53]. Approximately 90% of U.S. sweet corn acreage is treated with herbicides. Figure A26 charts herbicide use on U.S. sweet corn over time. It has been estimated that without herbicide use, U.S. sweet corn production would decline by 25% [5].

A.37 Sweet Potatoes

The two leading sweet potato production states are North Carolina and Louisiana. Approximately 70% of the sweet potato acreage in these states is treated with herbicides [12]. Because of the vining nature of sweet potatoes, cultivation for weed control can be used only during the first four weeks after transplanting, to avoid undue mechanical injury to the crop [6]. In the past, cultivation was supplemented with hand weeding late in the season [7]. However, due to the increased cost and scarcity of labor, sweet potato acreage declined in Alabama and Louisiana in the 1960s and 1970s, due to the tremendous amount of labor required for weed removal [8] [9]. Studies of labor requirements, for various tasks in growing sweet potatoes, showed that it took about 24 hours per acre to hoe the weeds [11].

Research demonstrated that recommended herbicides for sweet potatoes could reduce hoeing time by more than 30 hours per acre [10]. Without the use of herbicides, it has been estimated that sweet potato production would decline by 20% in the U.S. [5].

A.38 Tomatoes

In the early 1960s, California processed tomato growers relied on cultivation and hand hoeing for weed control. The typical processed tomato acre was cultivated three to six times, while nine to 16 hours were required for hand hoeing weeds [174] [175]. Despite these control measures, California processed tomato production was reduced by 10% in 1964; weed competition, reduction in stand, reduction in yield, and increased harvest cost and tomatoes left in the field because the harvesters could not find them in the dense weed growth caused the reduced yield [176] [177]. The development of mechanical harvesting, and the practice of seeding to a stand resulted in a necessity of improving weed control and reducing hand hoeing. Weeds had to be controlled for the mechanical harvesters to work efficiently [178]. Unless acceptable weed control was possible with a herbicide, it would not be economical to use precision seeding, since the hand weeding crews would reduce the tomato stand along with the weed removal process [179]. Direct seeding produced higher yields due to higher plant populations per acre [66]. UC farm advisors conducted 12 herbicide evaluation trials in 1968-1970, in cooperation with growers throughout California. More than 40 different herbicide treatments were evaluated [179]. Commercially acceptable weed control was obtained with diphenamid, trifluralin, pebulate, and napropamide [178]. In 1970, 87% of California’s processed tomato acreage was treated with herbicides [180]. The extensive use of herbicides, in combination with mechanical harvesting, resulted in the complete mechanization of growing processed tomatoes in California by the early 1970s [180].

A recent University of California analysis of organic processing tomato production in the Sacramento Valley indicated that the average acre is cultivated six times, and 15 hours were spent per acre for hand weeding [181]. An eight-year comparison of organic and conventional processing tomato production in California indicated that tomato yields were 17% lower in the organic system [194]. Weed abundance was found to be associated consistently over the years with the reduced crop yields in the organic system. Hand weeding was also largely responsible for the overall increased production cost of the organic system [194].

A recent study from USDA estimated that without herbicides, California's processed tomato production would decline by 20%, with the primary substitutes being increased cultivation and hand weeding [182]. A recent study by Texas A& M University estimated that without herbicides, California's processed tomato production would decline by 25%, despite increased hand weeding (+37 hours/acre) and increased cultivation (+eight trips/acre) [53].

Prior to the development of herbicides, tomato growers in eastern and midwestern states relied on hand weeding and cultivation for weed control [183]. Even with these methods, subsequent high-weed populations forced tomato growers in Florida to abandon cultivated fields after five or six years, and move to new land [184]. As labor for hand weeding became more expensive and less readily available, research focused on herbicides as possible replacements [183]. In Florida, three cultivations reduced weed populations by approximately 68% (from 2.5 million weeds/acre to .8 million weeds per acre) while early research with herbicides provided 79% control (to .5 million weeds per acre) [184]. In the early 1970s, the standard practice in eastern and midwestern tomato fields was the use of trifluralin pre-plant, followed by two cultivations and hand weeding [183]. In a 1978 experiment in Ohio with typical weed populations, the combination of two cultivations and 167 hours of hand weeding per hectare produced equivalent yields to an application of trifluralin, followed by two applications of metribuzin [183]. In New Jersey experiments in 1983/84, two cultivations plus 182-259 hours of hand weeding per acre produced tomato yields equivalent to herbicide treatments that included trifluralin and metribuzin [83].

An organic tomato grower in New Hampshire reports on the need for 11 hours of labor per acre for four cultivation trips and for the laying of black plastic down the row of tomato plants to smother weeds [299]. The black plastic cost is $200 per acre.

If eastern and midwestern fresh market tomato growers stopped the use of herbicides, the primary replacements would be hand weeding and cultivation, with an expected yield loss of 56% [182]. Approximately 96% of U.S. tomato acreage is treated with herbicides [16]. Nationally, it is estimated that tomato yields would decline by 23% without herbicides [5] [182].

A.39 Wheat

Approximately one-half of the winter wheat acres in the Central Great Plains is treated with herbicides [117]. Drought is normal in all semiarid regions of the Central Great Plains. Conservation of precipitation is of utmost importance for successful wheat production [398]. Weeds use water that could be used by the crop. Winter wheat competes well with most weeds [392]. Sown during the fall, wheat emerges and becomes established when most weeds are inactive. Following dormancy during winter, spring growth starts early and generally is rapid enough to provide vigorous competition for most annual weeds [392]. Early harvest enables wheat to avoid competition from many summer-growing weeds. Certain situations present serious weed problems in winter wheat. When soil moisture is deficient, wheat may not germinate uniformly, and a poor stand results. Some years, insects and diseases are factors. Thin stands enable weeds to become established during both fall and spring [392].

Prior to the introduction of herbicides in the 1940s, hand pulling of weeds in wheat fields was a common practice [393]. Winter wheat growers began using herbicides, particularly in years of subnormal rainfall, when thin stands led to a proliferation of weeds [394]. Herbicides were also used for control of perennial weeds such as field bindweed. The primary herbicides used in winter wheat have been the phenoxy herbicides (2,4-D and MCPA), which provide low cost post-emergence control of broadleaf weeds. A four-year study showed that wheat yields increased by 3.8 bushels per acre when 2,4-D was used [401]. Aerial application of 2,4-D is commonly used as a harvest aid treatment during years where broadleaf weeds threaten harvesting of the grain [398]. Winter wheat fields are usually prepared before planting with tillage for weed control. However, the narrow spacing of wheat planting means that cultivation during the season is not feasible [393]. Recently, there has been an increase in herbicide use in Great Plains wheat states (see Figure A27) as growers have begun adopting reduced-till and no-till production methods, and also have substituted herbicides for the pre-plant tillage [395]. One factor that has led to adoption of reduced till and no-till has been a major reduction in the price of glyphosate [395]. Tillage promotes soil drying. The use of herbicides to replace mechanical tillage prior to planting wheat improves water storage. Perennial grass and broadleaf weed species often become established in areas when tillage is reduced [398]. Another factor that led to greater herbicide use in Great Plains winter wheat areas in the 1980s-1990s was the switch from tall cultivars that compete well with weeds to higher yielding (+30%) semi-dwarf cultivars [66]. This switch led to an increase in certain weed problems such as downy brome, cheat and wild buckwheat [398]. The high-yielding semi-dwarf wheat varieties are disadvantaged competitors with weeds in comparison to the taller wheat varieties. Research showed a 363 kg/ha yield reduction in the semi-dwarf and 155kg/ha reduction in the normal height wheat, with no weed control compared to a weed free check [399]. Wheat growers could switch back to taller varieties, but yield would be lower [396]. For major Great Plains wheat states, yields are projected to decline in an average year by 7-10% without herbicides [5]. However, without herbicides, some growers would experience a complete loss in certain years [397]. Twenty-eight percent of the wheat acres in the Great Plains were abandoned and not harvested during 1936 to 1945. Over the next 4 decades, abandoned wheat acres decreased to 22%, 20%, 16% and 12%, respectively [400]. Without herbicides, it is projected that winter wheat growers in the Great Plains would cultivate three additional times for control of weeds, particularly perennials, prior to planting and use 2 additional hours of labor for weed control [397].

The states in the Midwest and Northeast produce winter wheat. Between 40-60% of the wheat acres in the Midwest and Northeast are treated with herbicides. A higher proportion of no-till wheat acres have been established in the Midwest and Northeast, in comparison to the Great Plains. Prior to planting wheat, herbicides are used to remove winter annual weeds, which germinate as soon as adequate rainfall occurs in August and September [398]. Since winter wheat grows rapidly and is a highly competitive crop, most Midwest/Northeast farmers do not routinely plan weed control programs in anticipation of serious infestations [398]. When abnormally heavy rains occur before harvest, wheat harvest may be delayed so long that weeds grow into the canopy of wheat heads. When wheat is weedy at harvest time, weeds are treated with 2,4-D, causing them to dry up and reduce harvesting problems [398]. A special weed problem in the Midwest/Northeast region is wild garlic and wild onion. If harvested and milled with wheat, they result in odors and off-flavors so that growers receive a lower price [398]. Herbicides are used to remove the wild garlic and onion plants prior to harvest. Prior to the development of herbicides, weeds in the Midwest increased combine losses by 13% because of poor grain separation from the straw [402]. Without herbicides, yield losses in Midwest and Northeast wheat are estimated at 10-50% [5].

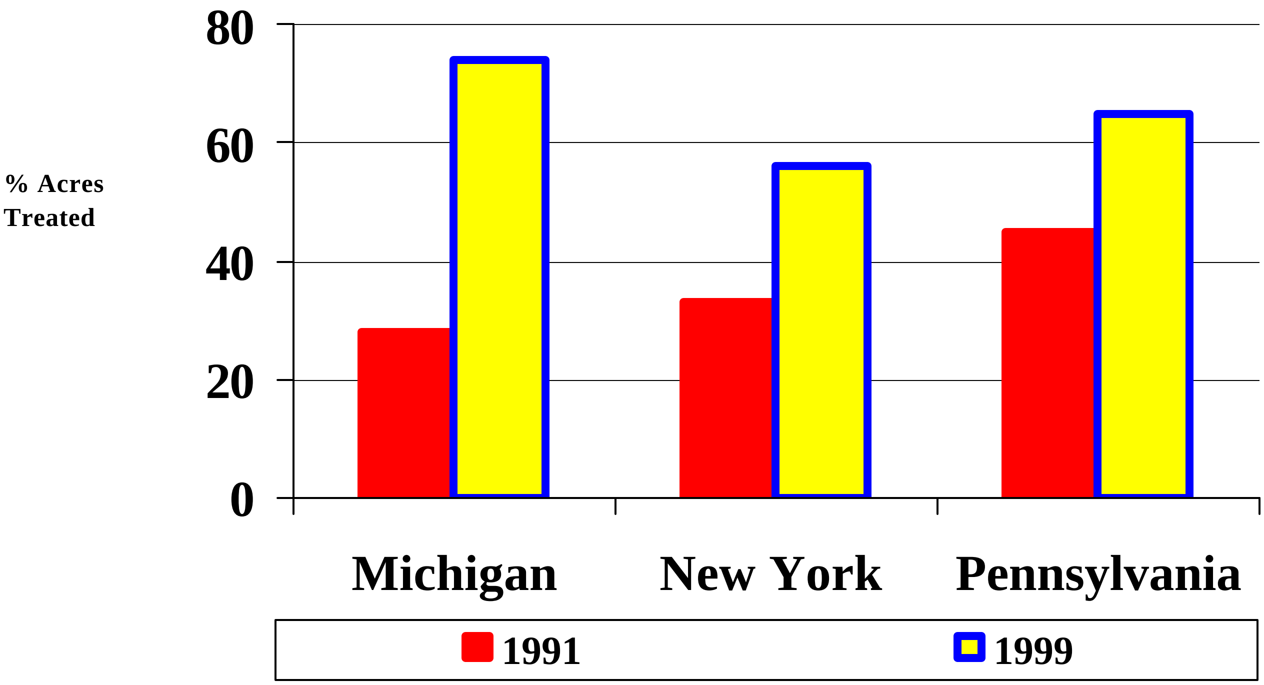
Annually, more than 90% of the winter wheat acreage in the Pacific Northwest is treated with herbicides. Figure A28 charts herbicide use in Washington wheat since 1949. Since the early 1970s, herbicides have been applied consistently to more than 90% of the wheat acreage in Washington. The Pacific Northwest region is characterized by humid winters and dry summers. The wet, mild winters are favorable for winter wheat production. Yields are among the highest in the U.S. Figure A29 charts the increase in Washington's wheat yields since 1947. The increased use of herbicides is partially credited for the increased wheat yields. Several dozen weed species thrive in conditions under which winter wheat is grown. Annual broadleaf weeds germinate just before or as the wheat germinates. Wheat fields frequently become a solid mat of well-established broadleaf weeds, if weed control practices are lacking [403]. If weeds are left uncontrolled, a large number of species could grow so large that harvesting would be impaired [398]. Russian thistle can significantly reduce wheat yields and harvest efficiency, and in some cases, completely prevent wheat harvest [404]. A major advance in weed control occurred in 1959 when diuron was introduced for selective weed control in winter wheat. Diuron adequately controlled Italian ryegrass and annual bluestem, as well as many species of broadleaf annuals [398]. Diclofop-methyl was instrumental in making significant inroads against wild oats. High potential yields and the severe competitiveness of weeds in the long mild season make herbicide use much more cost-effective than in other winter wheat growing regions. An organic wheat grower in Oregon reports that yields are 40-80% lower than conventional yields [309]. Without herbicides, wheat yields are projected to decline by 25-30% in the Northwest [5].

Spring wheat is planted in states (ND, SD, MT, MN) where winters are severe which would result in the freezing and death of wheat planted in the fall. Spring wheat varieties are planted from late-April to the end of May, and are harvested in the fall, from early August to late September. In these four states, the temperate summer climate is ideal for growing wheat. Herbicides are used on more than 90% of the wheat acres in the spring wheat states. Figure A28 charts herbicide use in North Dakota since 1949. A majority of the wheat acres have been treated with herbicides since the 1960s. Figure A29 shows average wheat yields in North Dakota since 1949. There is a corresponding increase in yield associated with the increase in herbicide use. Annual broadleaf weeds (kochia, wild mustard), annual grassy weeds (foxtails, wild oats), and perennial broadleaves (Canada thistle, bindweed) infest wheat fields throughout the four Northern Plains states. Left unchecked, 10 wild oat or wild mustard plants per square foot will reduce wheat yield by 35%. Two or three kochia plants per square foot can reduce yields by 30%. Wild oat germinates quickly in the spring and can compete out wheat, resulting in severe wheat yield loss. Delayed seeding was recommended in the 1940s and 1950s to reduce wild oat infestation in spring wheat. By delaying seeding, wheat yields were reduced by 15% [405]. Delayed seeding was also relatively ineffective in controlling wild oats because the weed continues to emerge throughout the early summer, even if wheat is seeded very late in the first week of June after repeated spring tillage to stimulate wild oat germination [398]. Wild oat, wild mustard and Russian thistle are much less a problem now because of the use of herbicides [398]. Without herbicides, wild mustard would be likely to cause more than a 36% reduction in wheat yields in infested spring wheat acres [406]. An experiment in North Dakota indicated that without weed control, wheat yield was 67% lower than when treated with standard herbicides [407]. With 222 hours of hand weeding per acre, wheat yields were 25% lower than with herbicide treatments [407]. Organic wheat yields are estimated to be 25% lower than conventional yields in North Dakota [260]. It has been estimated that without herbicides, average wheat yields in the Northern Plains states would be reduced by 30% [95].

A.40 Wild Rice

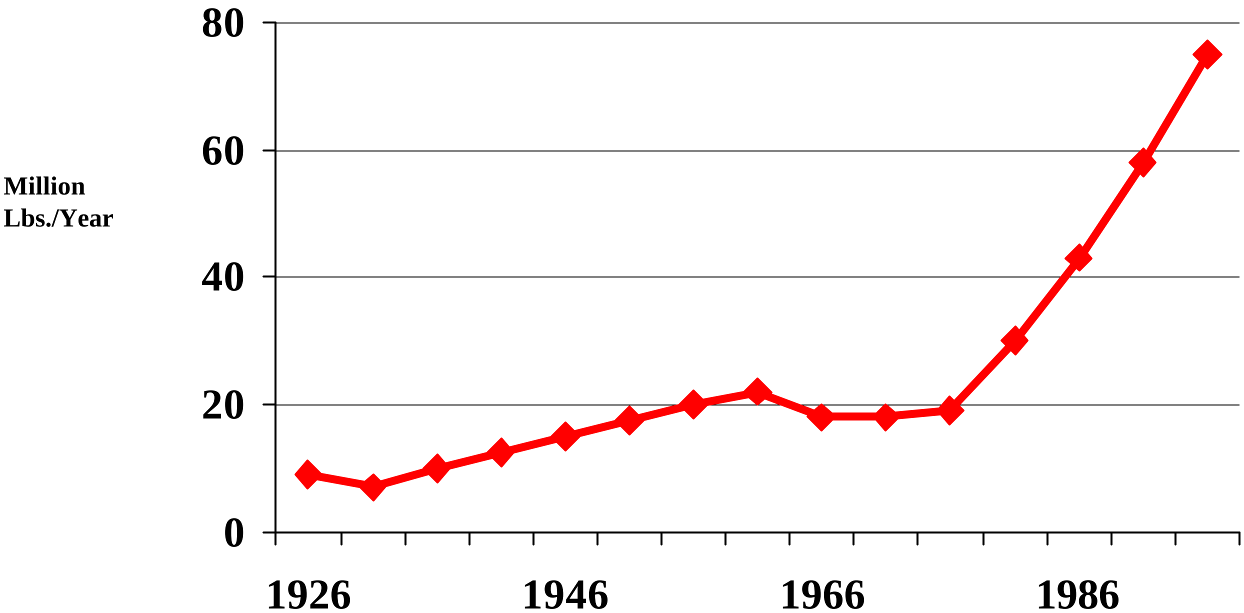
Wild rice is a cereal grain, which is native to Minnesota and has been successfully cultivated in the state since the 1960s. In the past, natural stands of this plant provided a staple in the diets of local Native American tribes. Because of the high capital investment associated with dike construction and irrigation equipment, and since land cultivated with wild rice is poorly suited for alternate crops, wild rice is commonly grown in the same field year after year [128]. This continuous monoculture has permitted the establishment of common water plantain at competitive levels in many fields. An average yield loss of 43%, with one plantain per square foot, was shown experimentally [126]. Hand weeding and cultivation are not possible because wild rice is grown in flooded paddies. The herbicide 2,4-D is the only herbicide that has been available to Minnesota wild rice growers and was available only because an emergency exemption was granted, specifically for the control of water plantain [126]. In its request to EPA for the emergency registration, the state of Minnesota estimated that without the herbicide, wild rice yields would decline by 50% on infested acreage [129]. It has been estimated that water plantain infests 10-50% of the acreage, and that 2,4-D is used on 10% of the acreage [126]. No alternative non-chemical weed control method would be used if 2,4-D were not available for Minnesota wild rice growers [393].

Figure A 1: Apple Herbicide Use



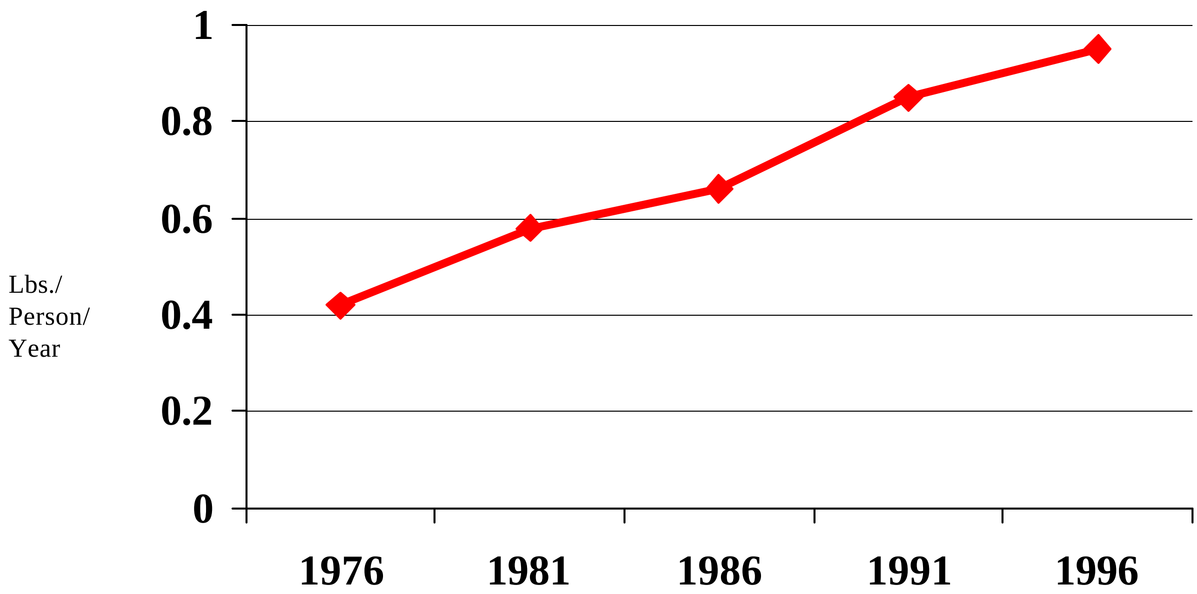
Source: [14]

Figure A 2: Maine Wild Blueberry Production



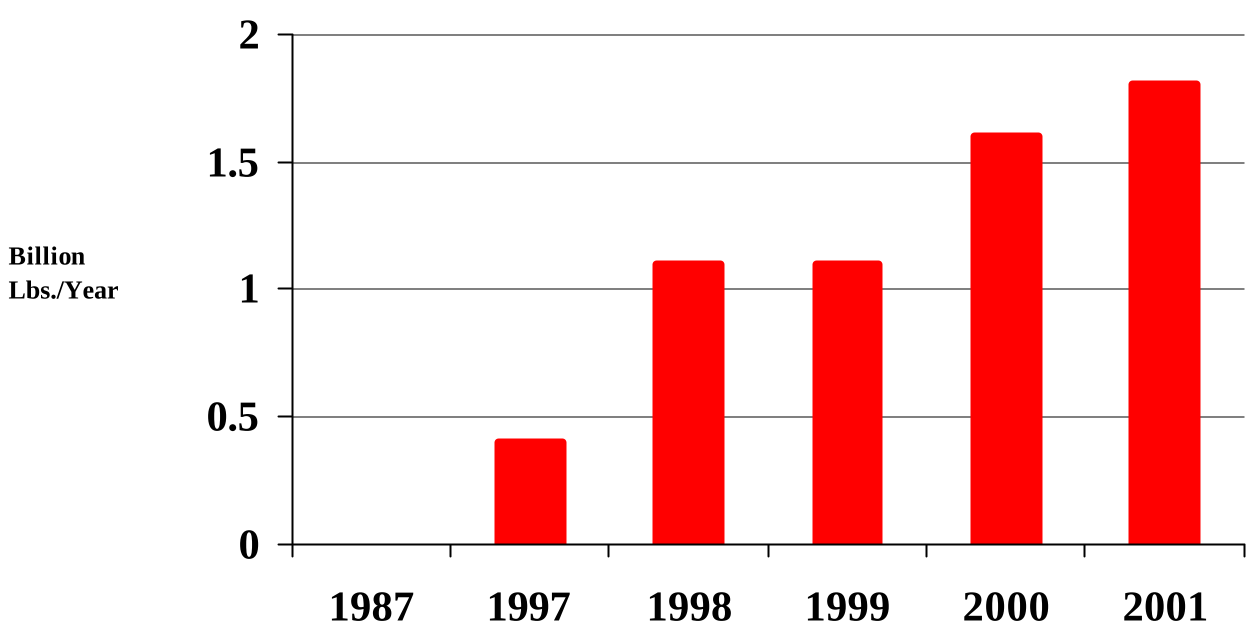
Source: [382]

Figure A 3: U.S. Blueberry Consumption



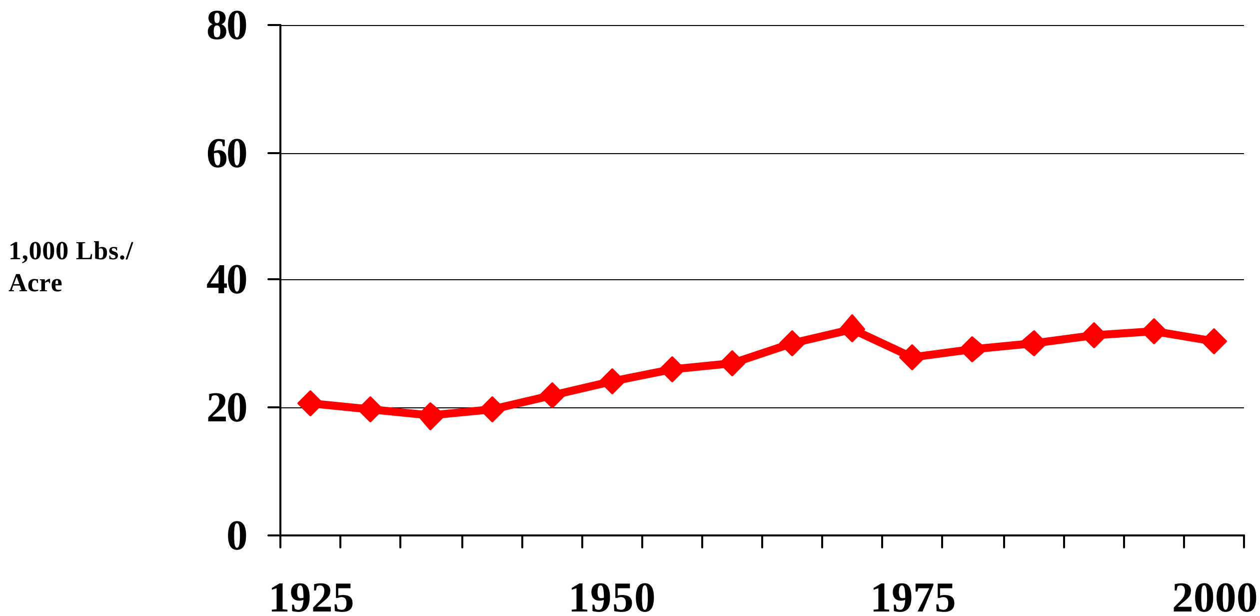
Source: [380]

Figure A 4: North Dakota Canola Production



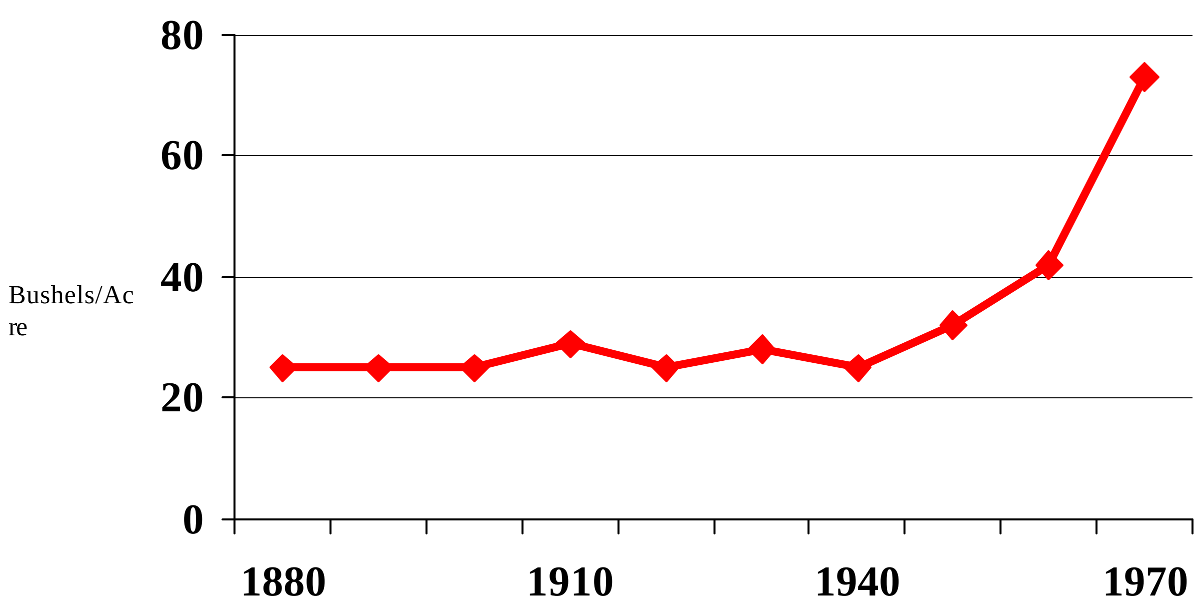
Source: [1]

Figure A 5: California Carrot Yield



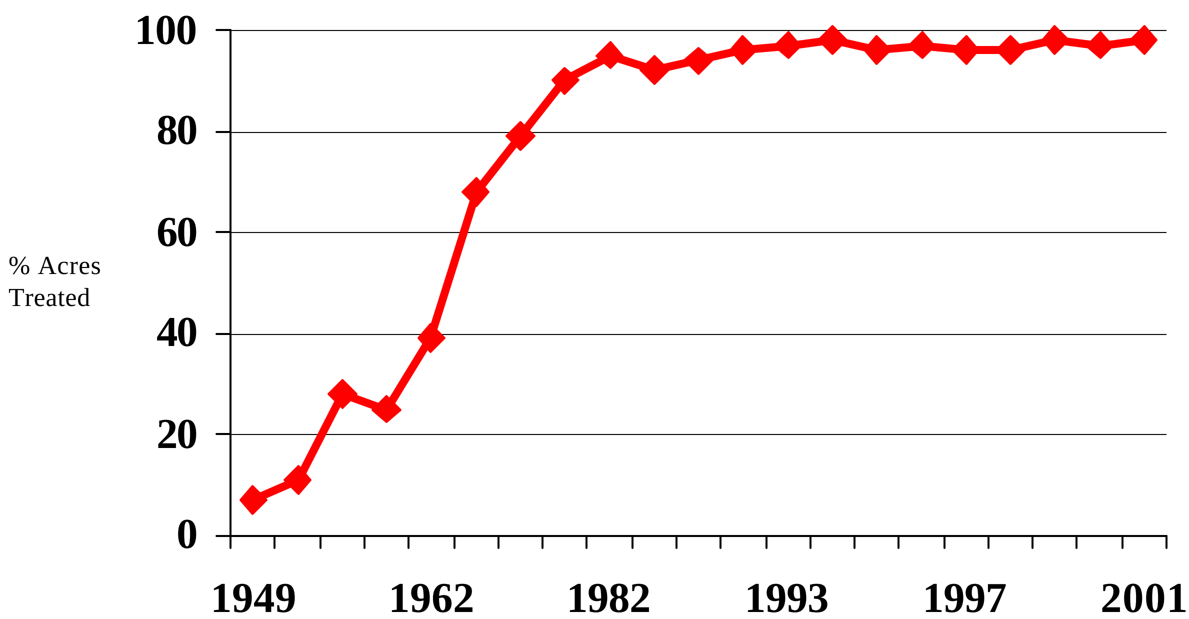
Source: [381]

Figure A 6: U.S. Corn Yields



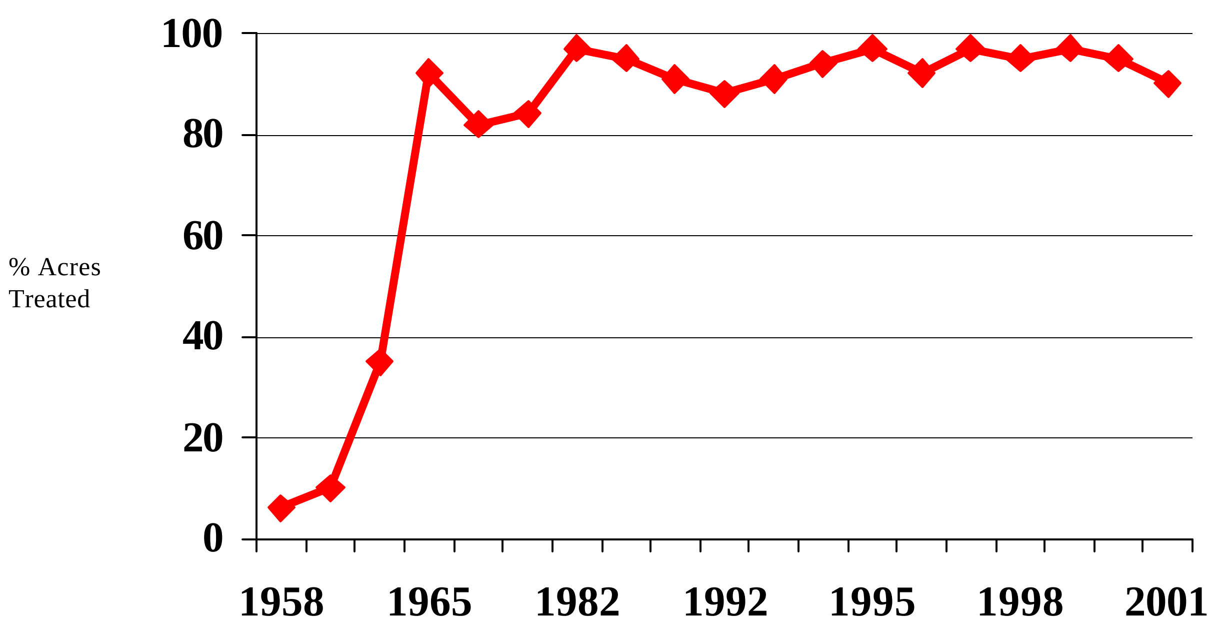
Source: [355]

Figure A 7: U.S. Corn Acreage Treated with Herbicides



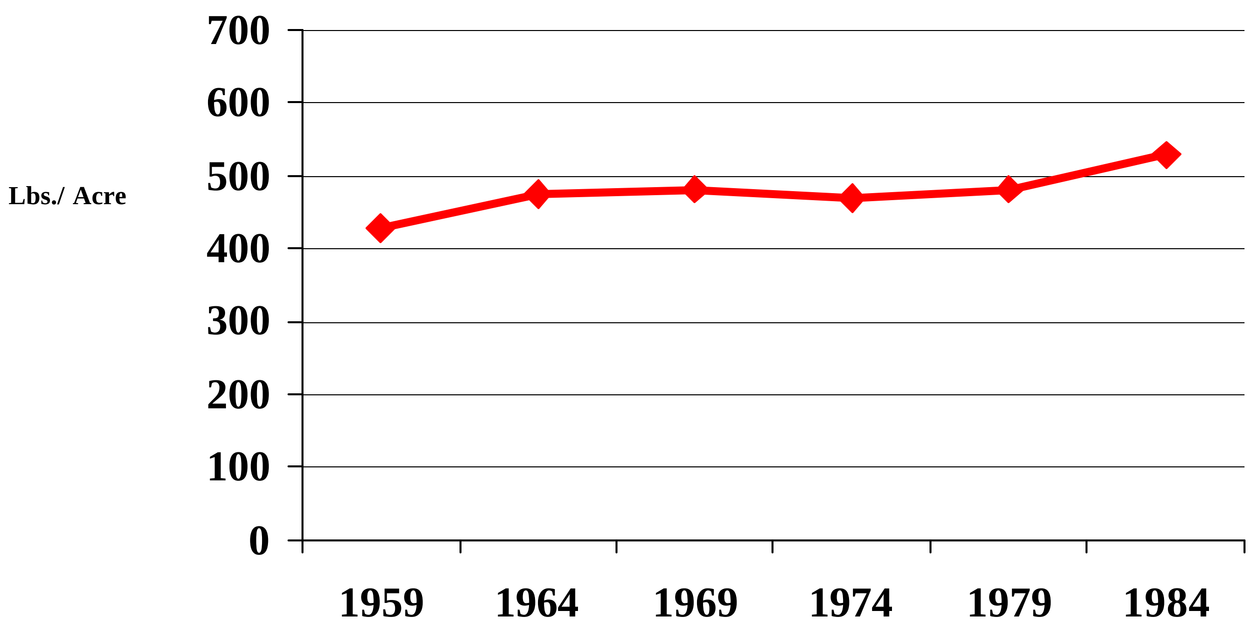
Source: [166]-[170][117][173]

Figure A 8: U.S. Cotton Acreage Treated with Herbicides



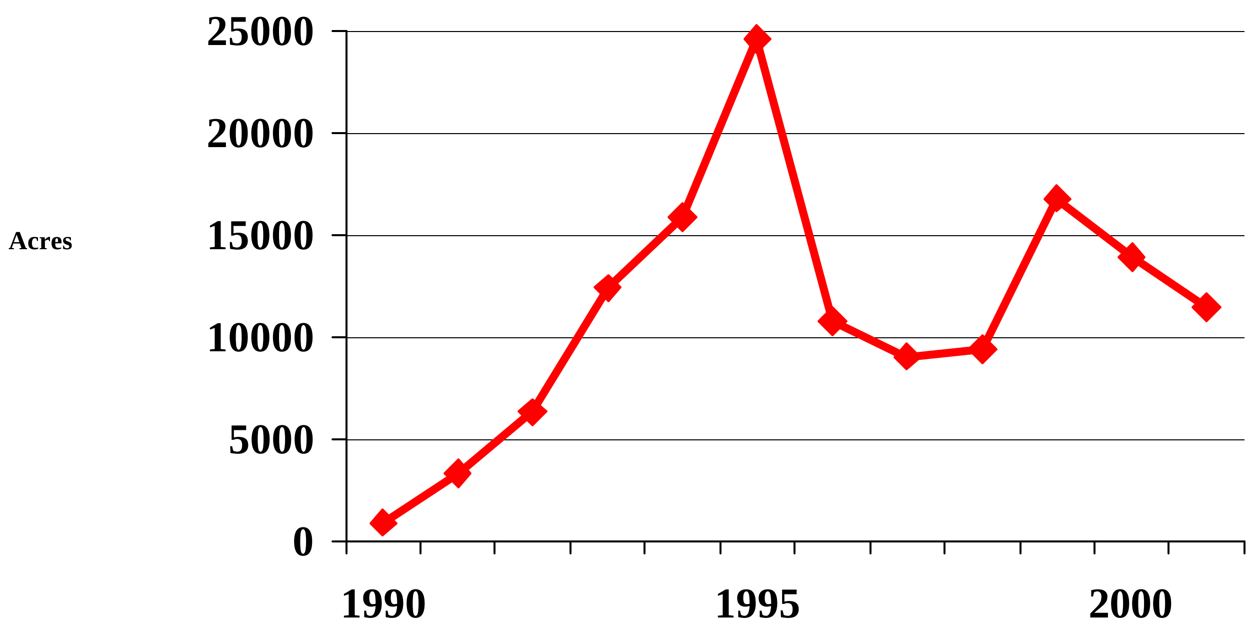
Source: [166]-[170][117][173]

Figure A 9: U.S. Cotton Yield



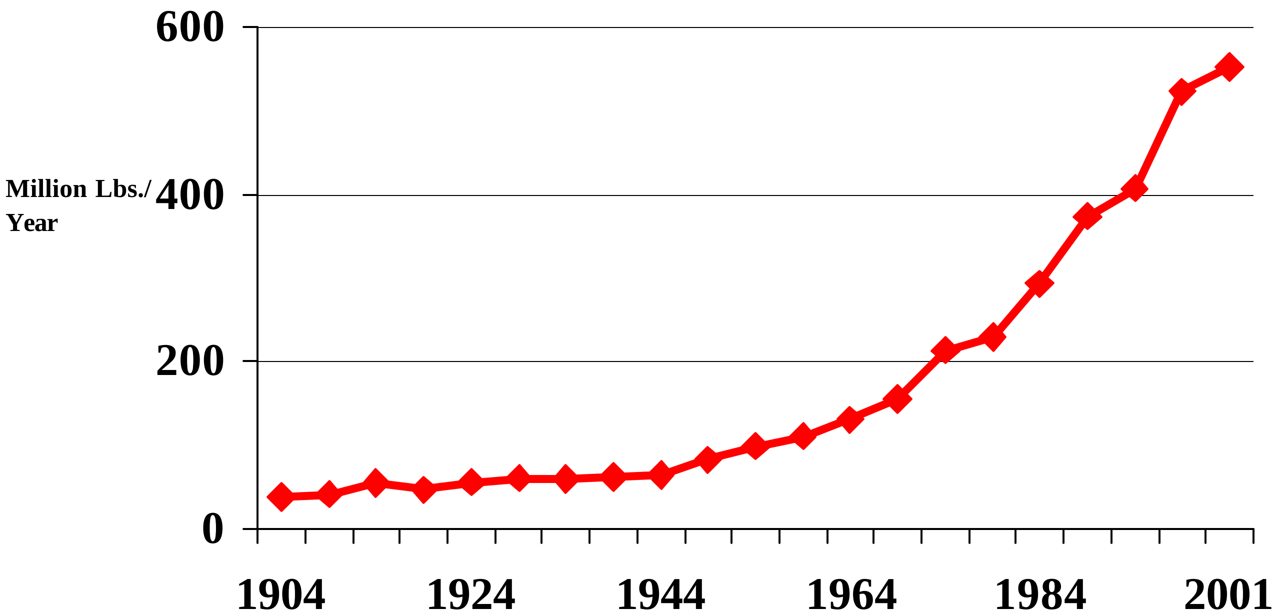
Source: [358]

Figure A 10: U.S. Organic Cotton Acreage



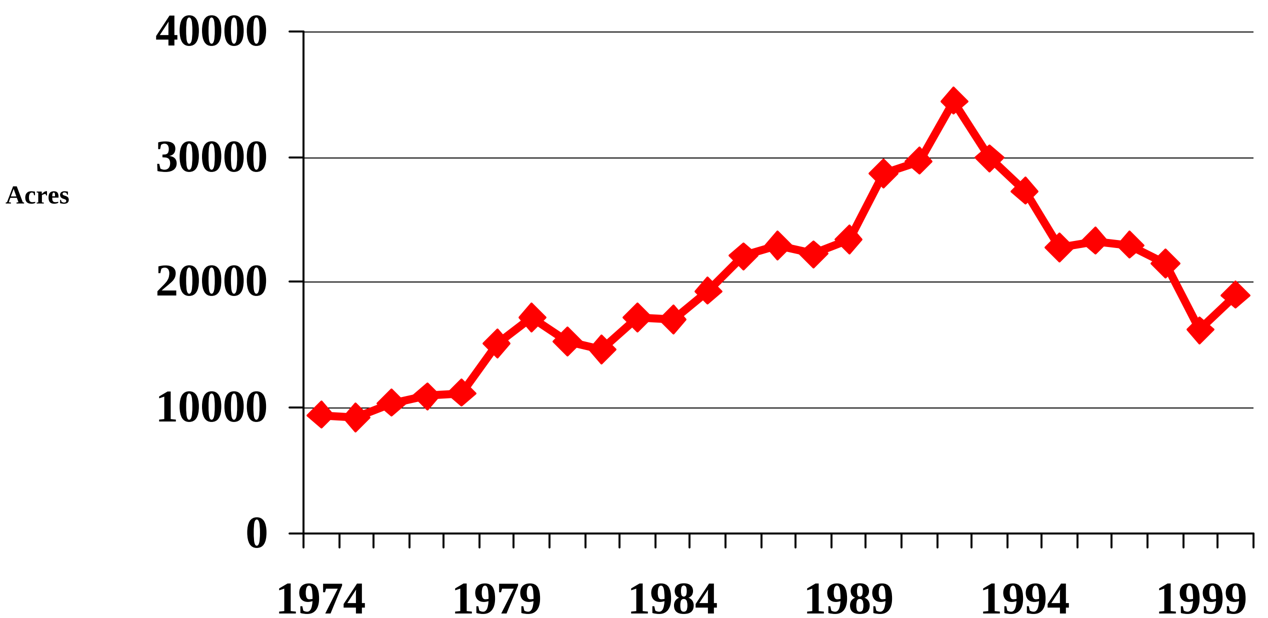
Source: [321]

Figure A 11: U.S. Cranberry Production



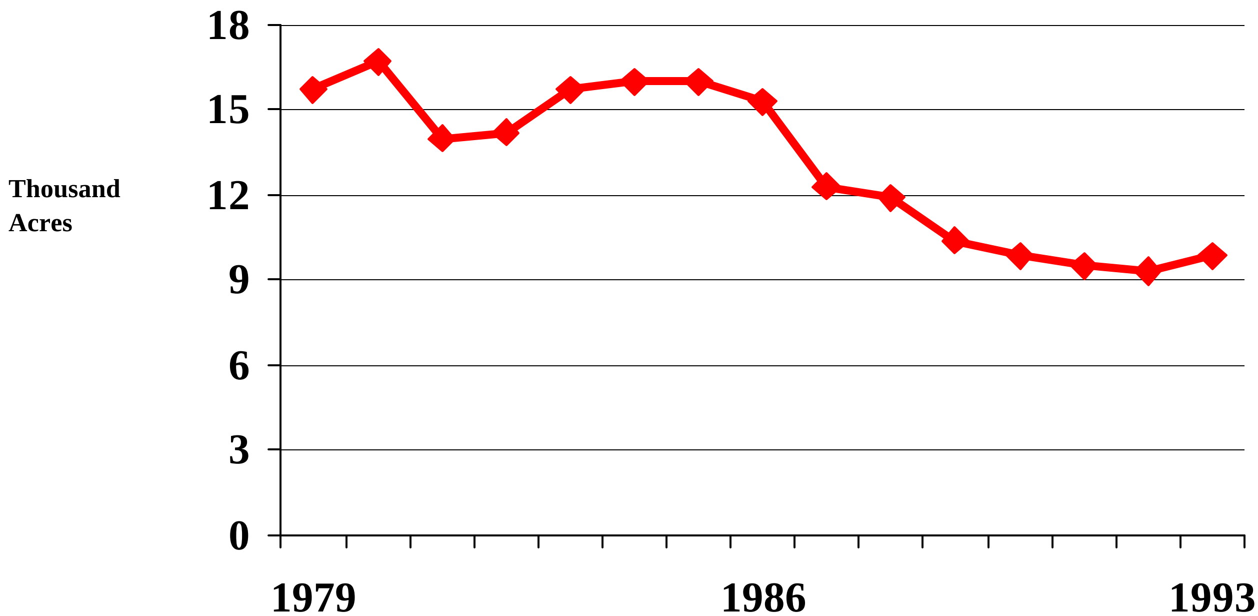
Source: [38][13]

Figure A 12: New Mexico Hot Pepper Acreage



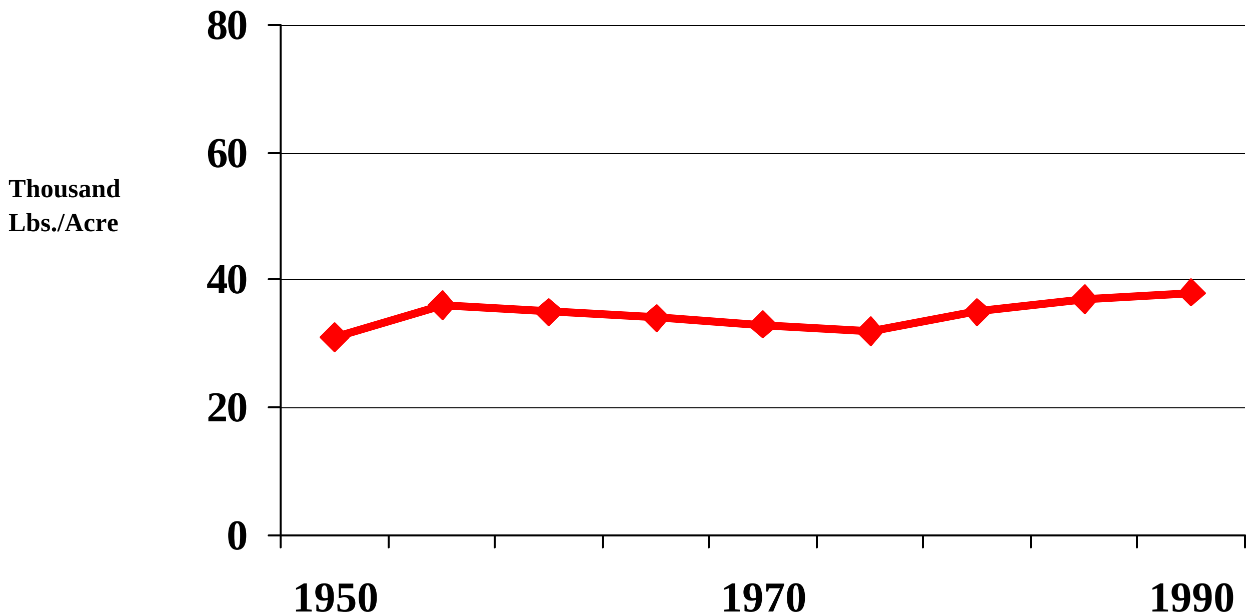
Source: [379]

Figure A 13: Florida Lettuce Acreage



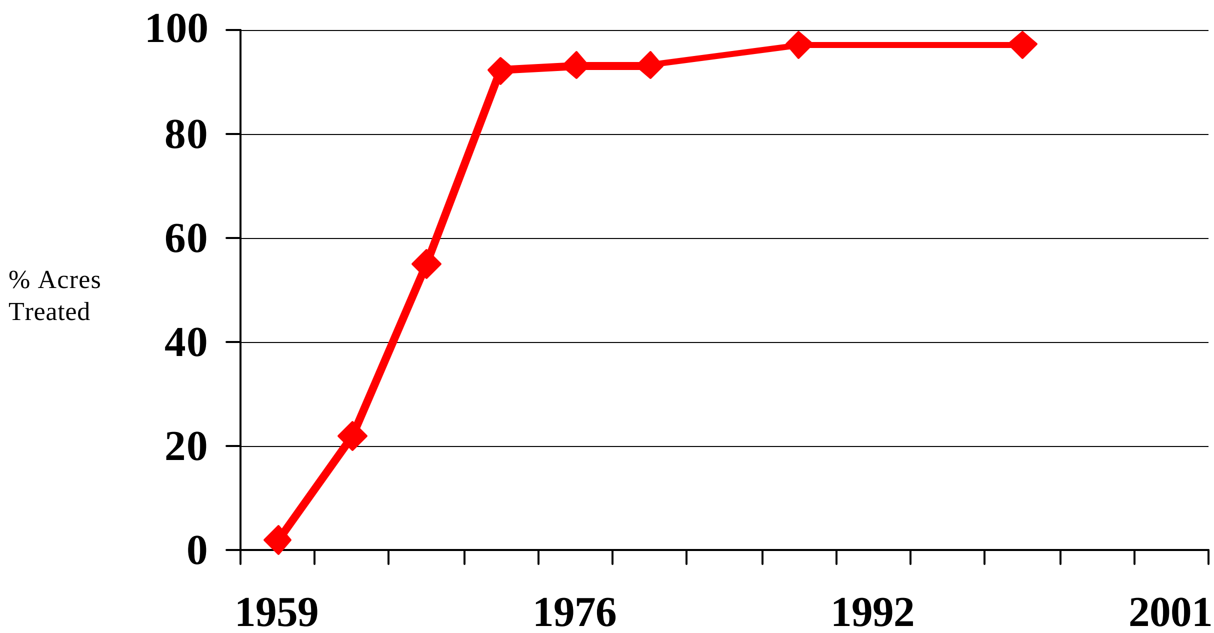
Source: [359]

Figure A 14: California Onion Yields



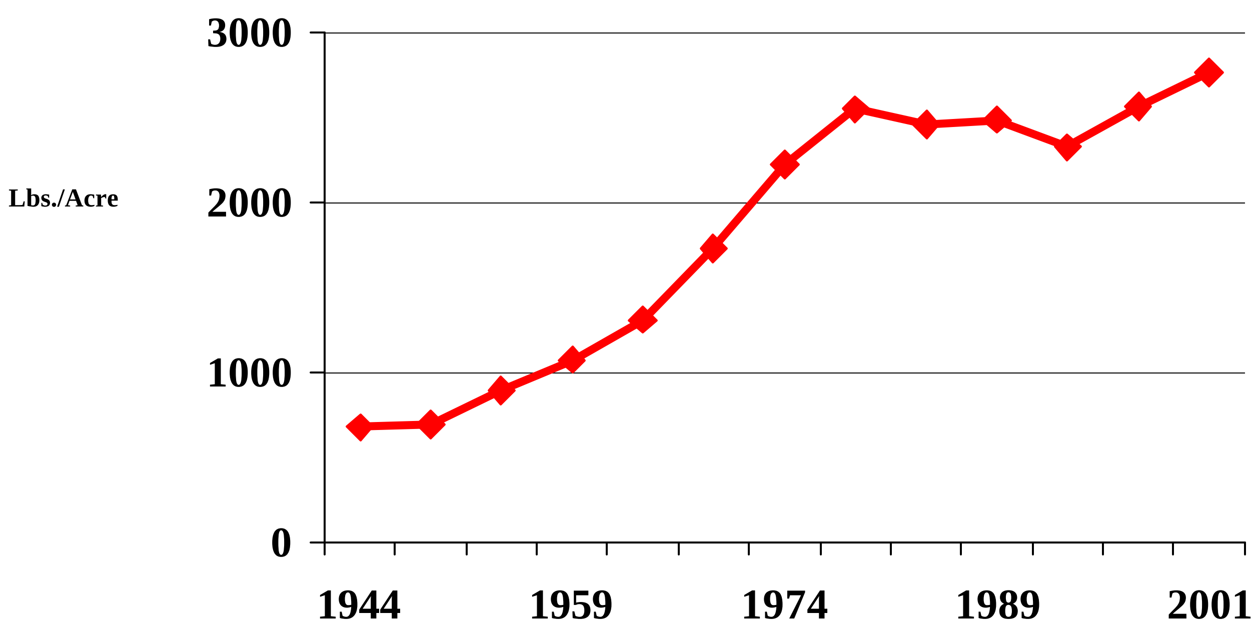
Source: [355][356]

Figure A 15: U.S. Peanut Acreage Treated with Herbicides



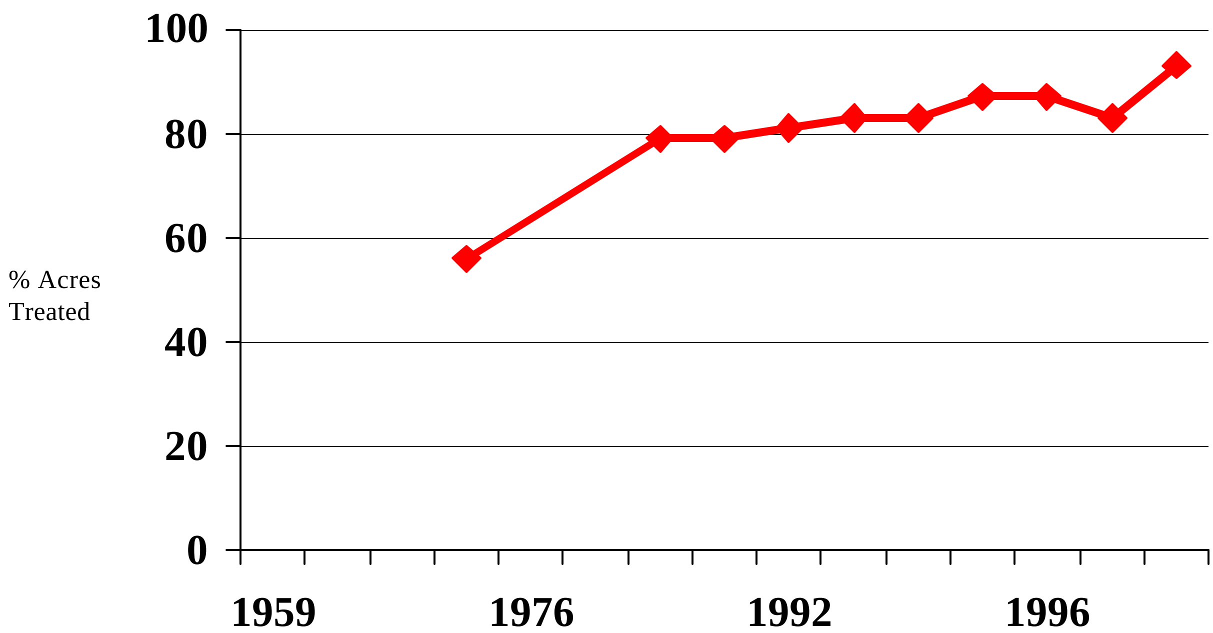
Source: [166]-[170][117][173]

Figure A 16: U.S. Peanut Yields



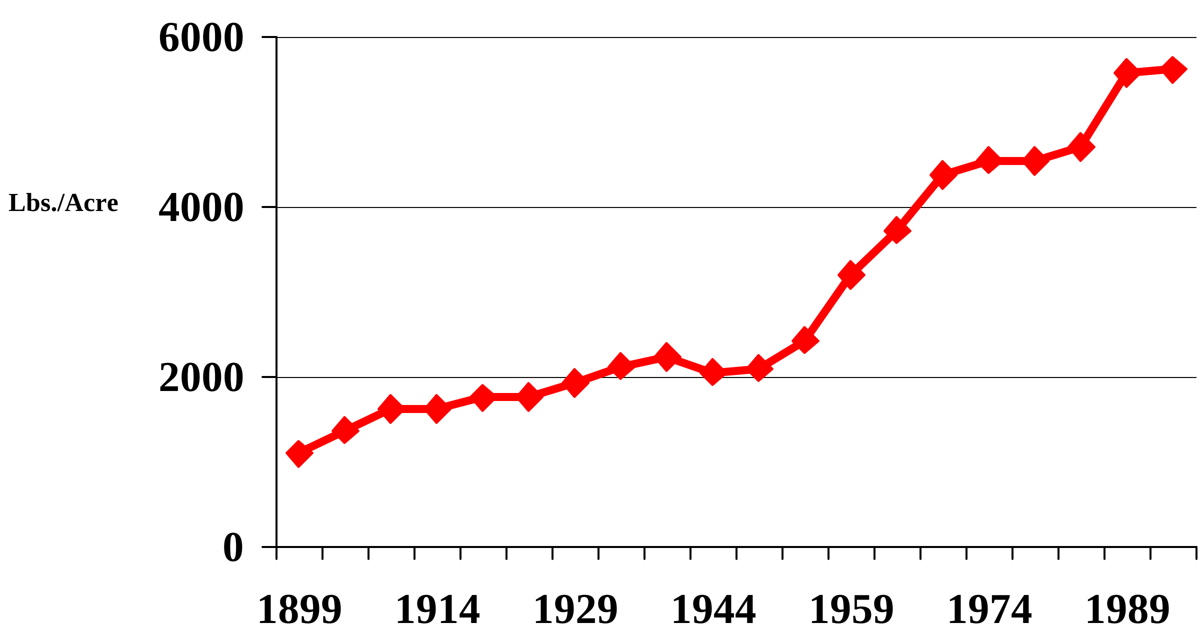
Source: [355]

Figure A 17: U.S. Potato Acreage Treated with Herbicides



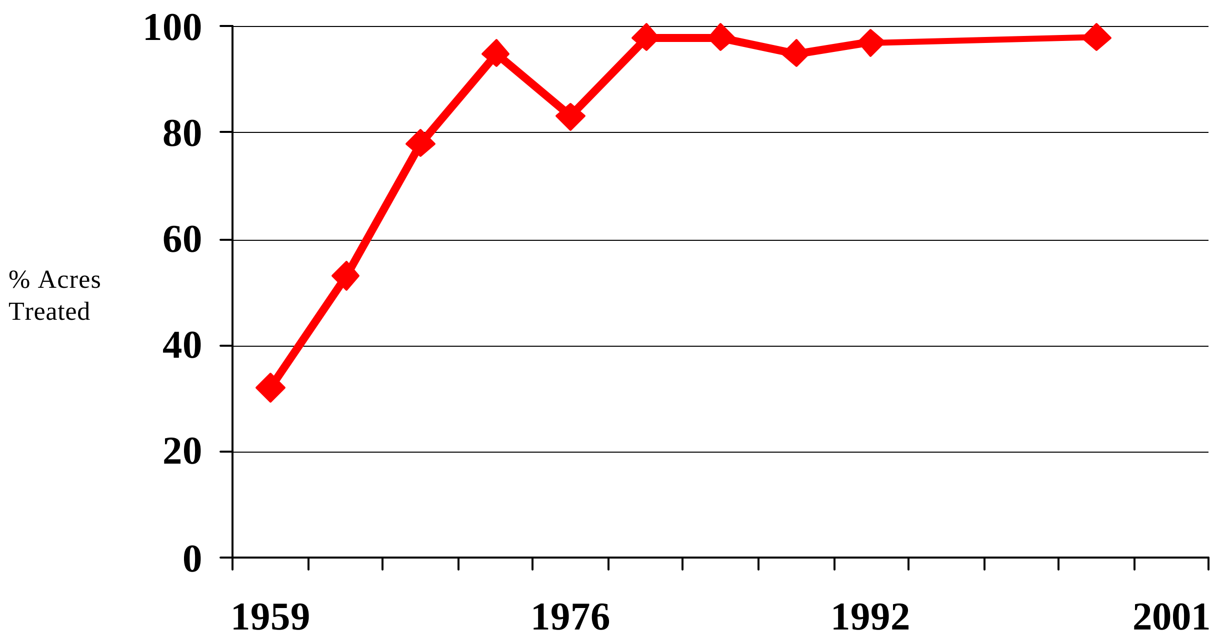
Source: [166]-[171][117][173]

Figure A 18: U.S. Rice Yields



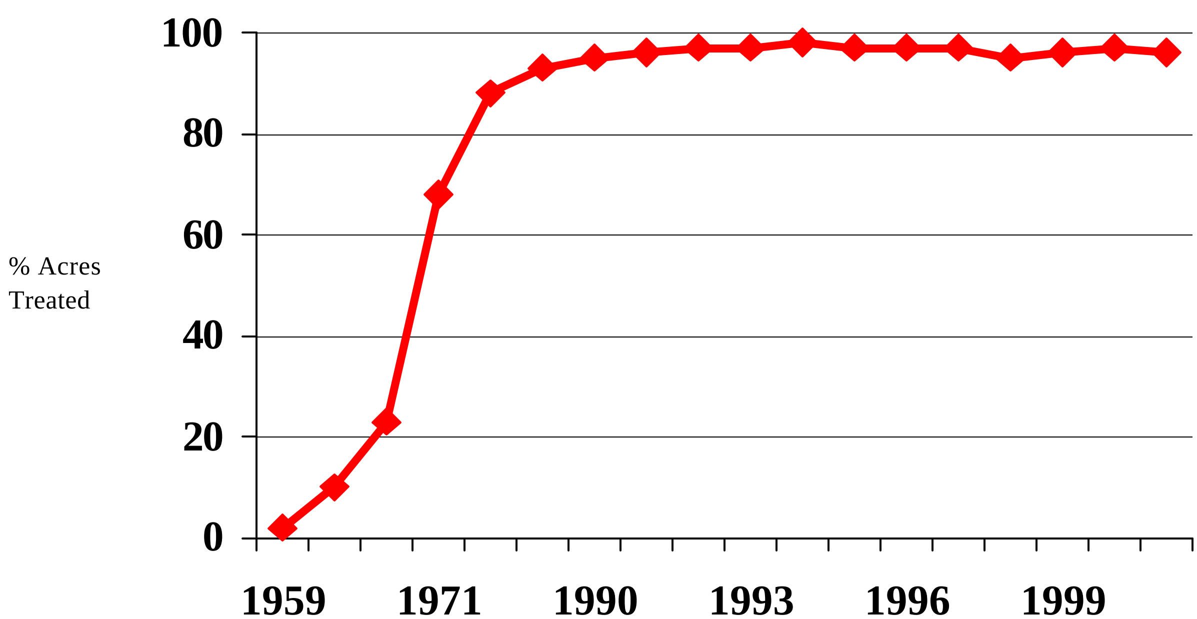
Source: [357]

Figure A 19: U.S. Rice Acreage Treated with Herbicides



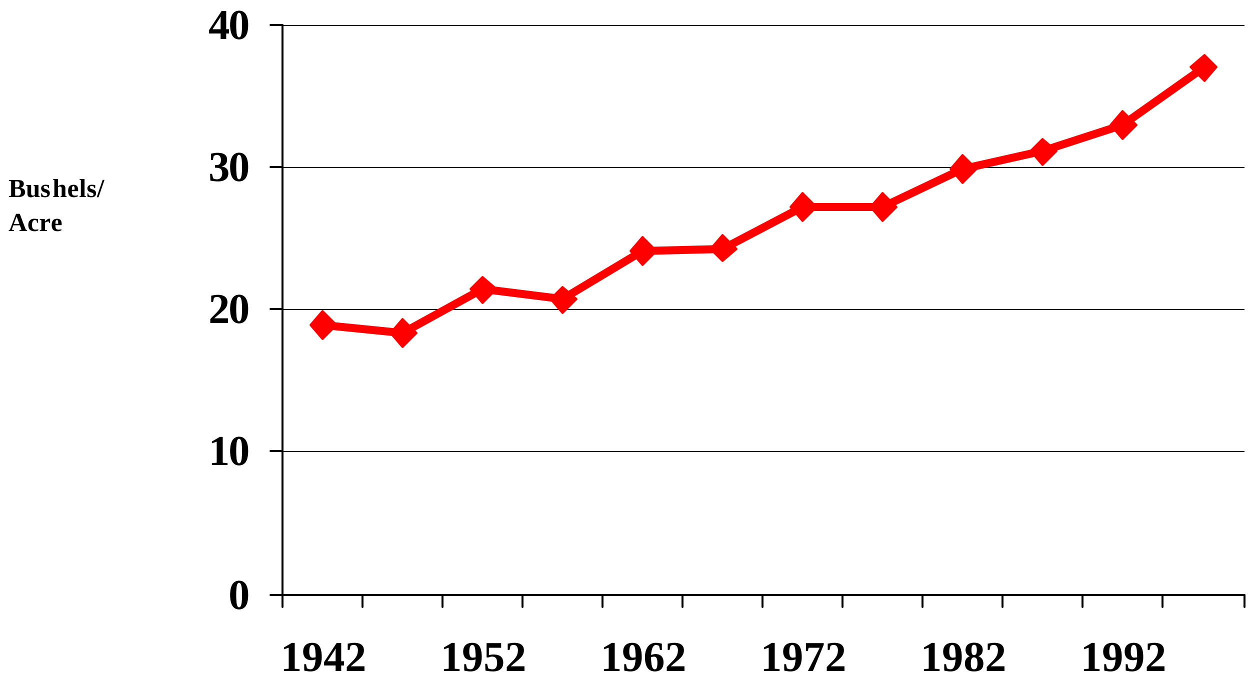
Source: [166]-[170][117][173]

Figure A 20: U.S. Soybean Acreage Treated with Herbicides



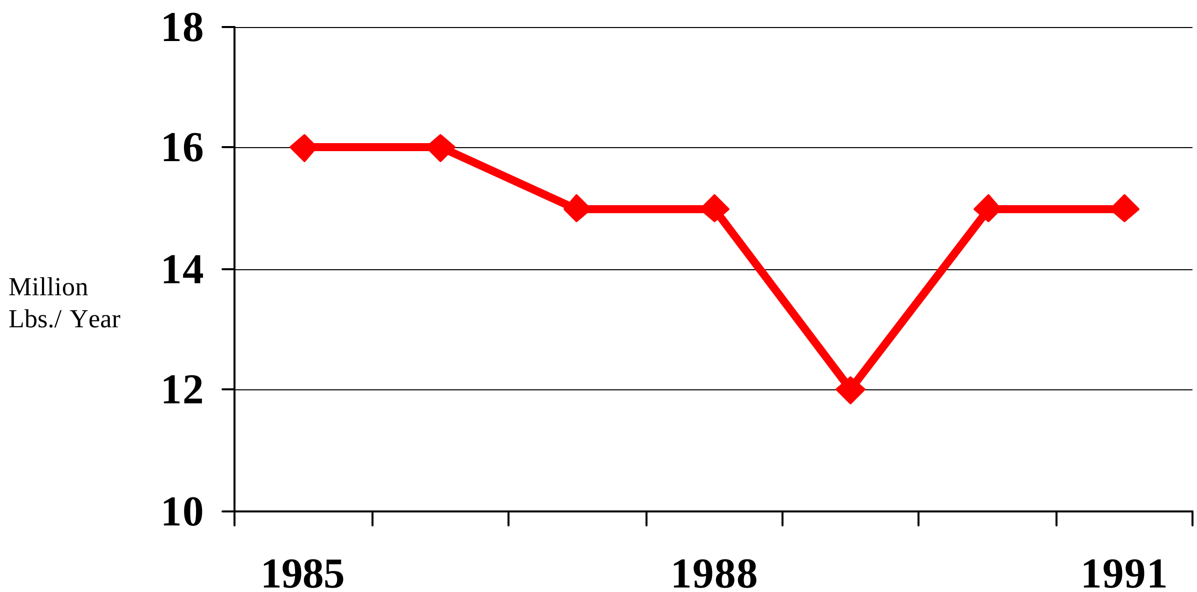
Source: [166]-[170][117][173]

Figure A 21: U.S. Soybean Yields



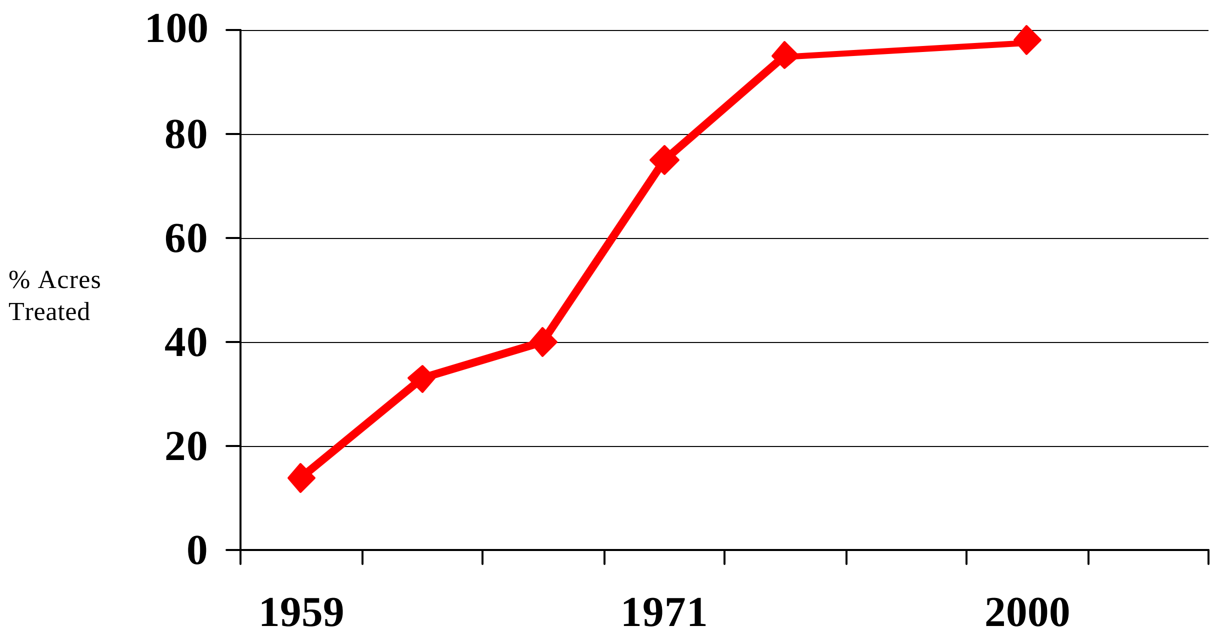
Source: [355]

Figure A 22: New Jersey Spinach Production



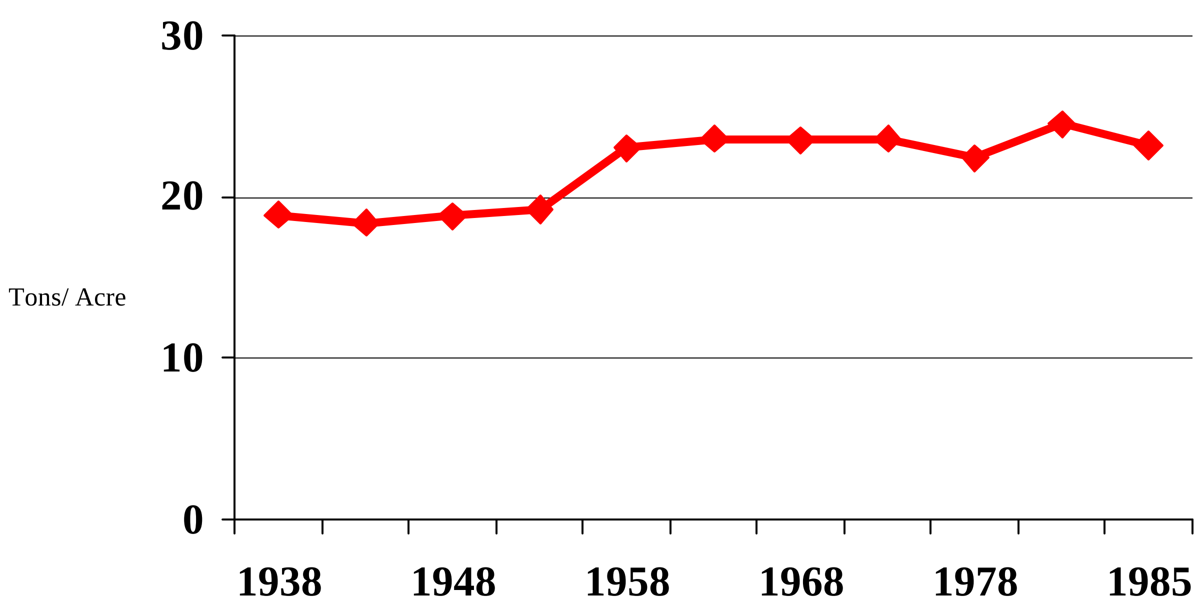
Source: [15]

Figure A 23: U.S. Sugarbeet Acreage Treated with Herbicides



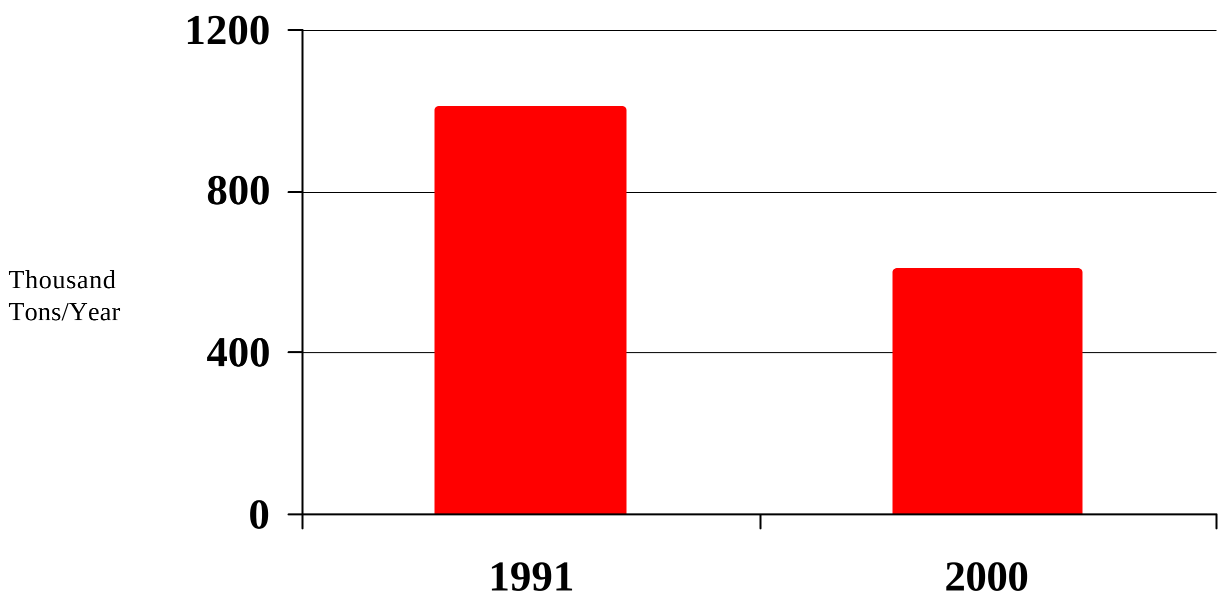
Source: [166]-[170][117][173]

Figure A 24: Louisiana Sugarcane Yield



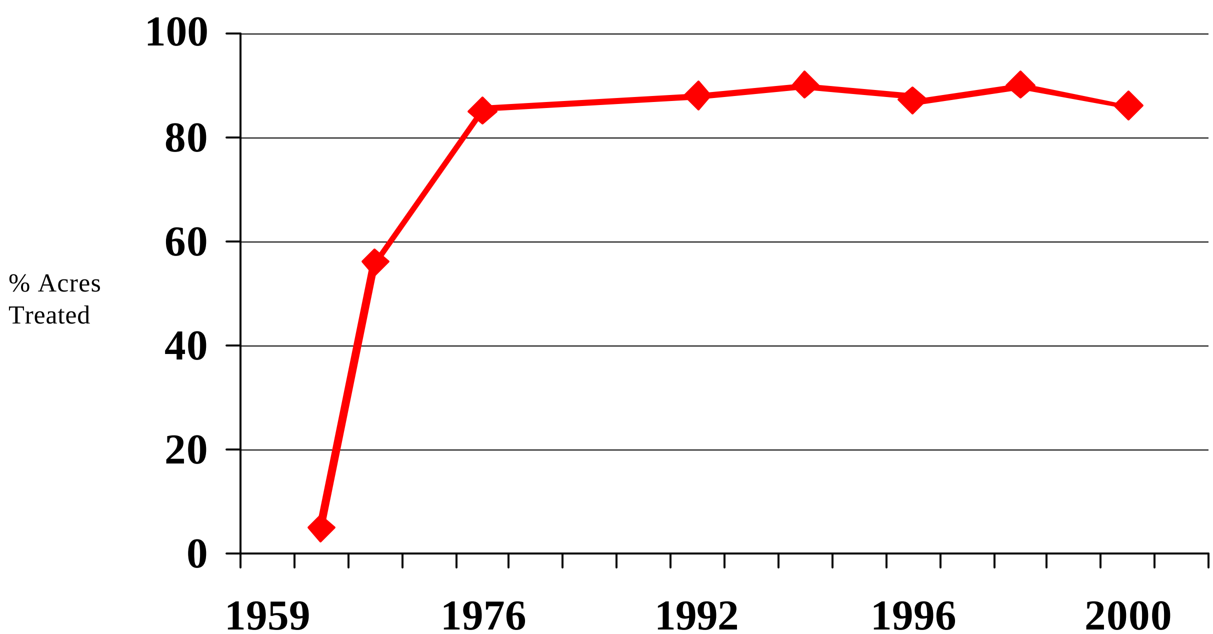
Source: [360]

Figure A 25: Wisconsin Sweet Corn Production



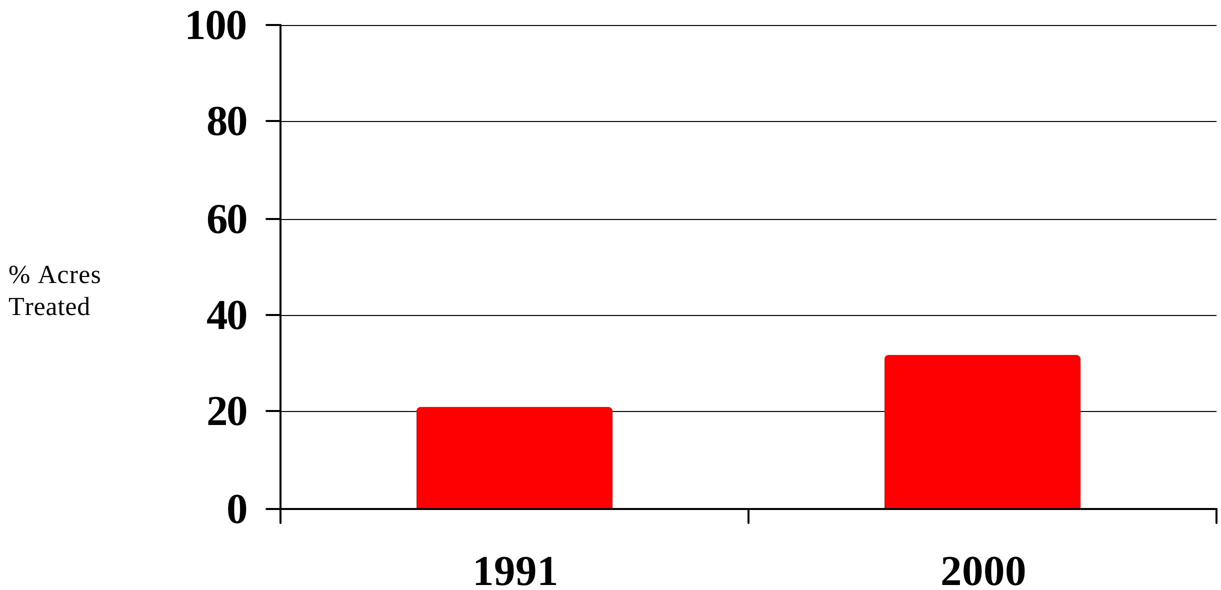
Source: [15]

Figure A 26: U.S. Sweet Corn Acreage Treated with Herbicides



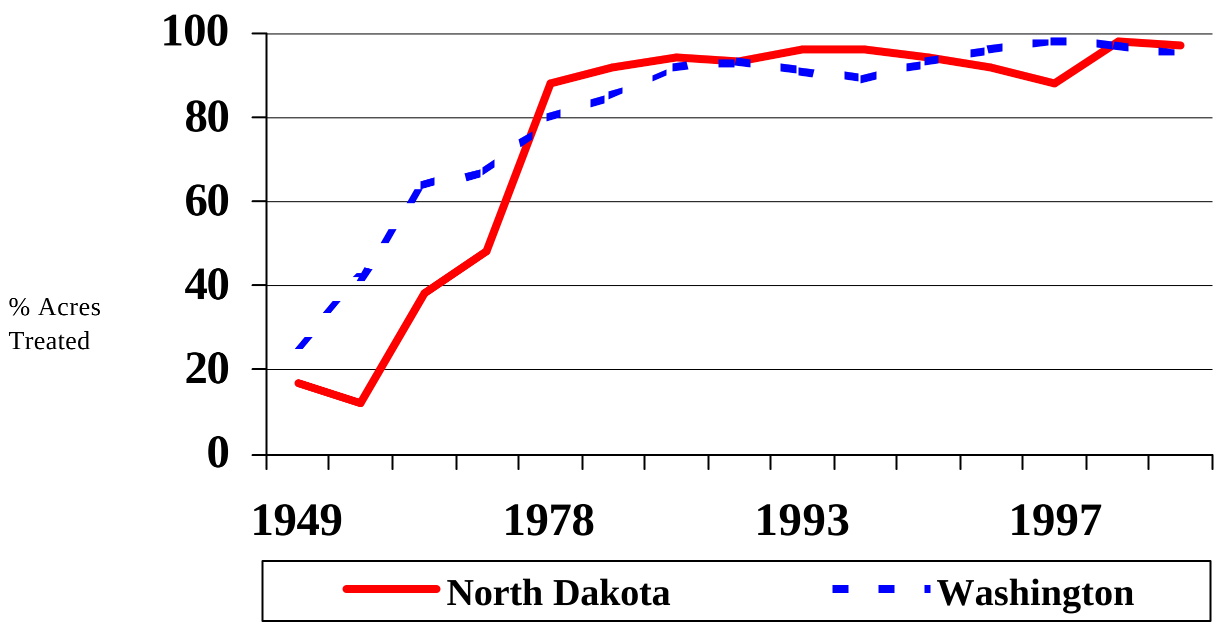
Source: [166]-[171][117][173]

Figure A 27: Kansas Wheat Acreage Treated with Herbicides



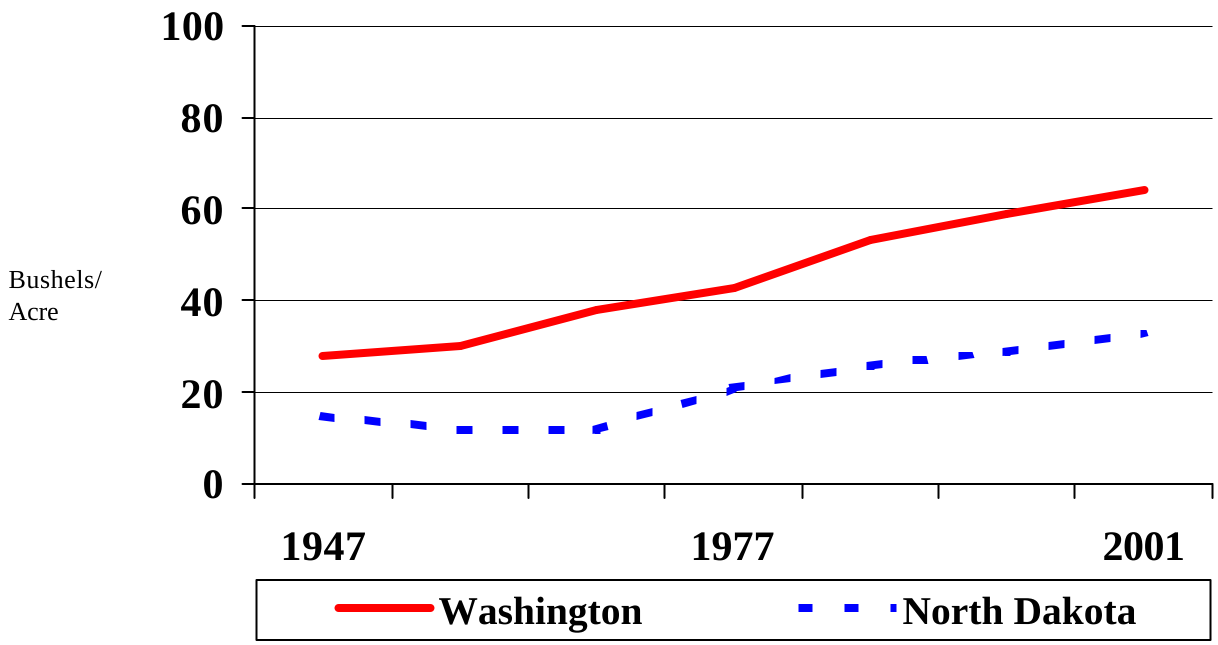
Source: [117]

Figure A 28: Wheat Acreage Treated with Herbicides



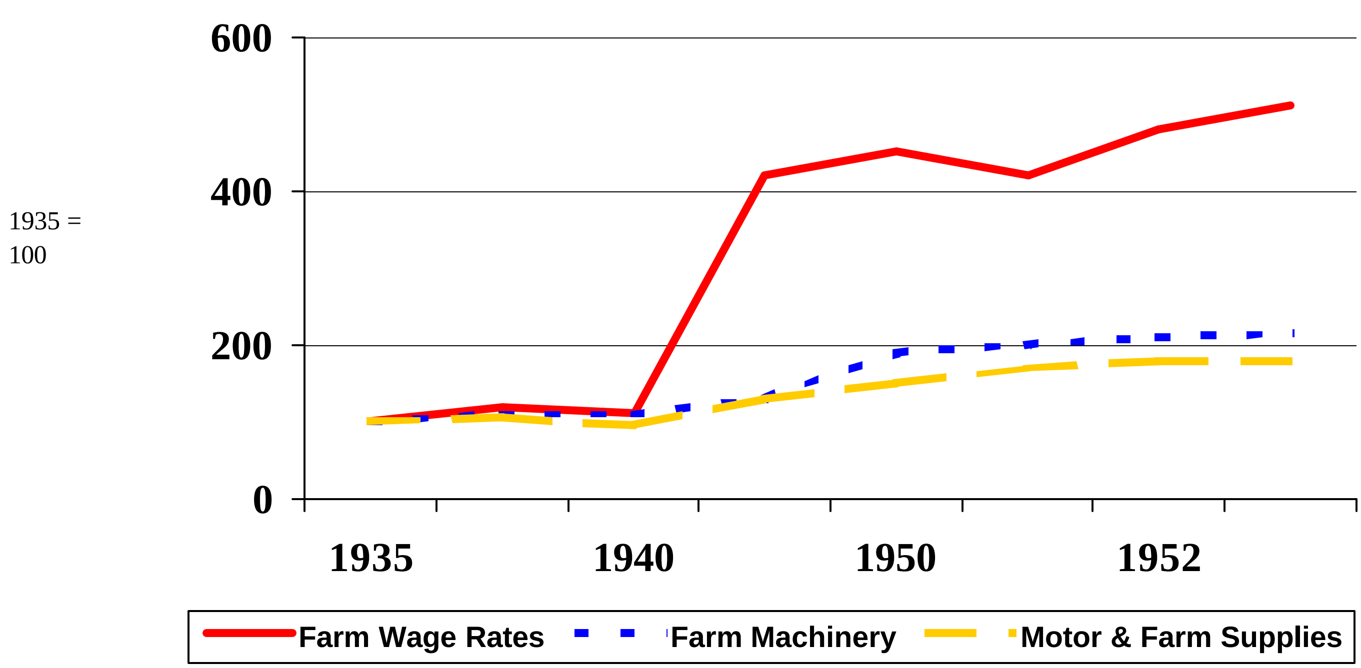
Source: [166]-[170][117][173]

Figure A 29: Wheat Yields, Selected States



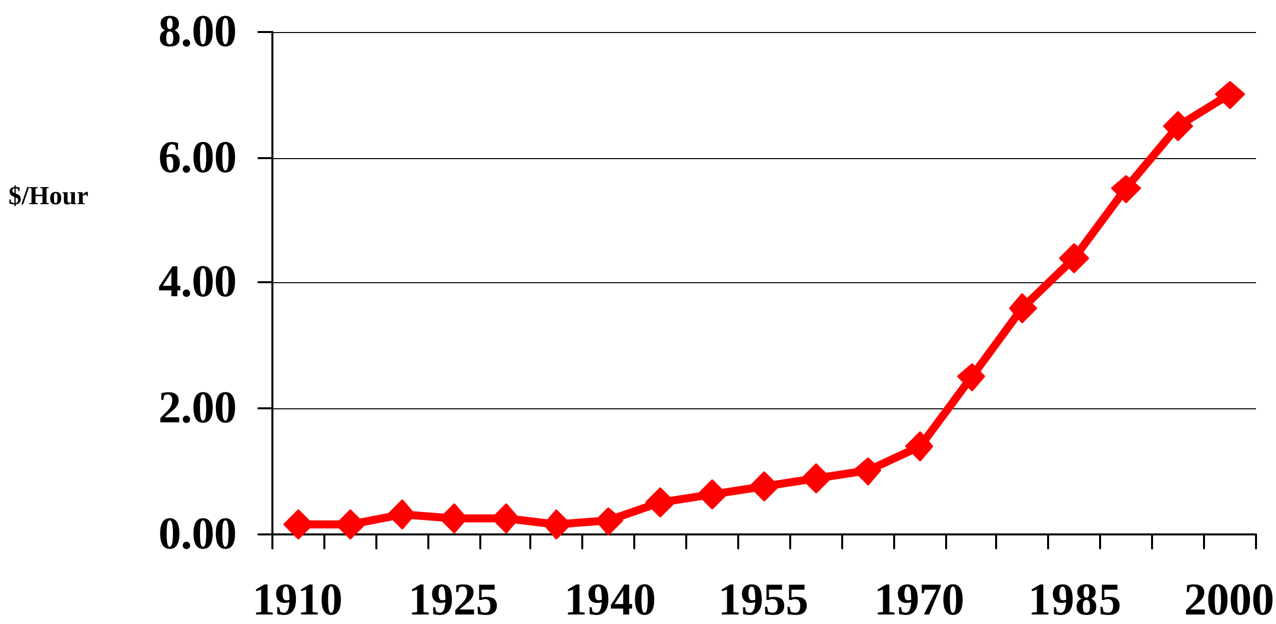
Source: [355][383][1]

Figure A 30: Indexes of Prices Paid by Farmers for Production Inputs



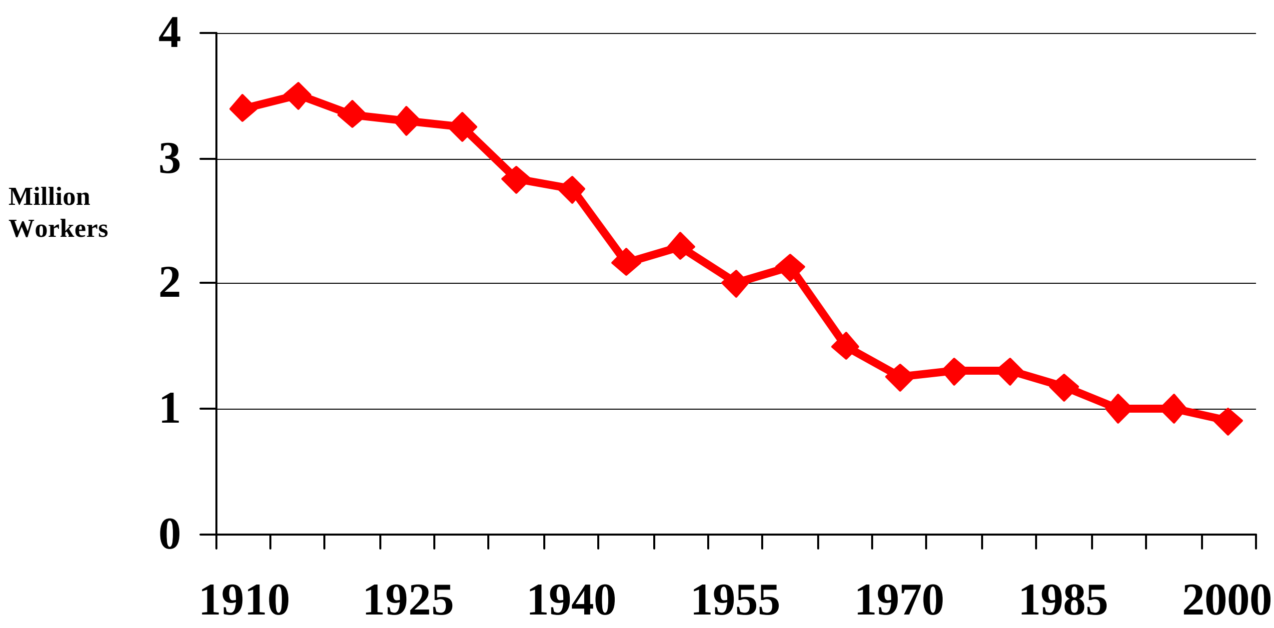
Source [295]

Figure A 31: U.S. Hired Farm Worker Wage Rate



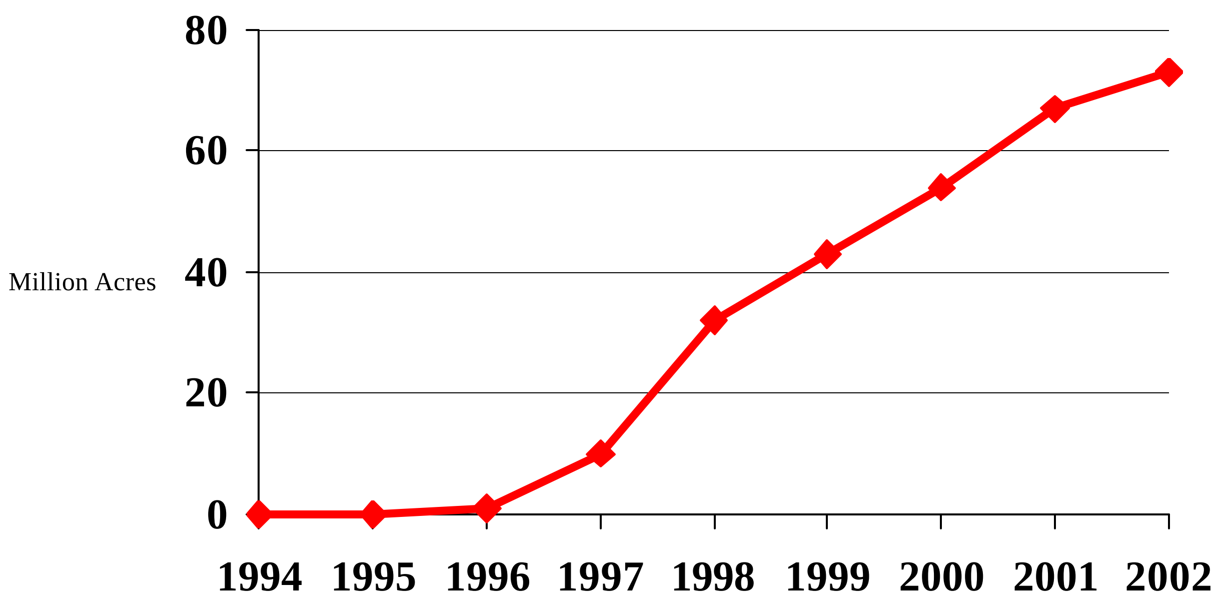
Source: [378]

Figure A 32: U.S. Hired Farm Workers



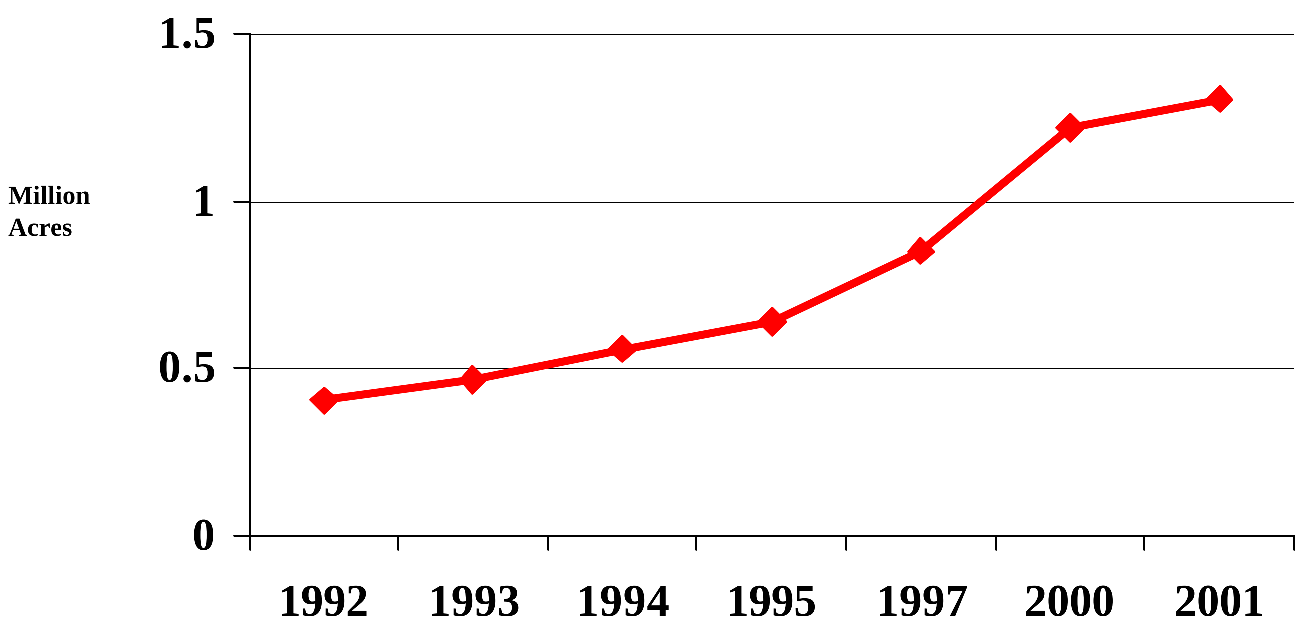
Source: [378]

Figure A 33: U.S. Biotech Herbicide Tolerant Crop Acreage



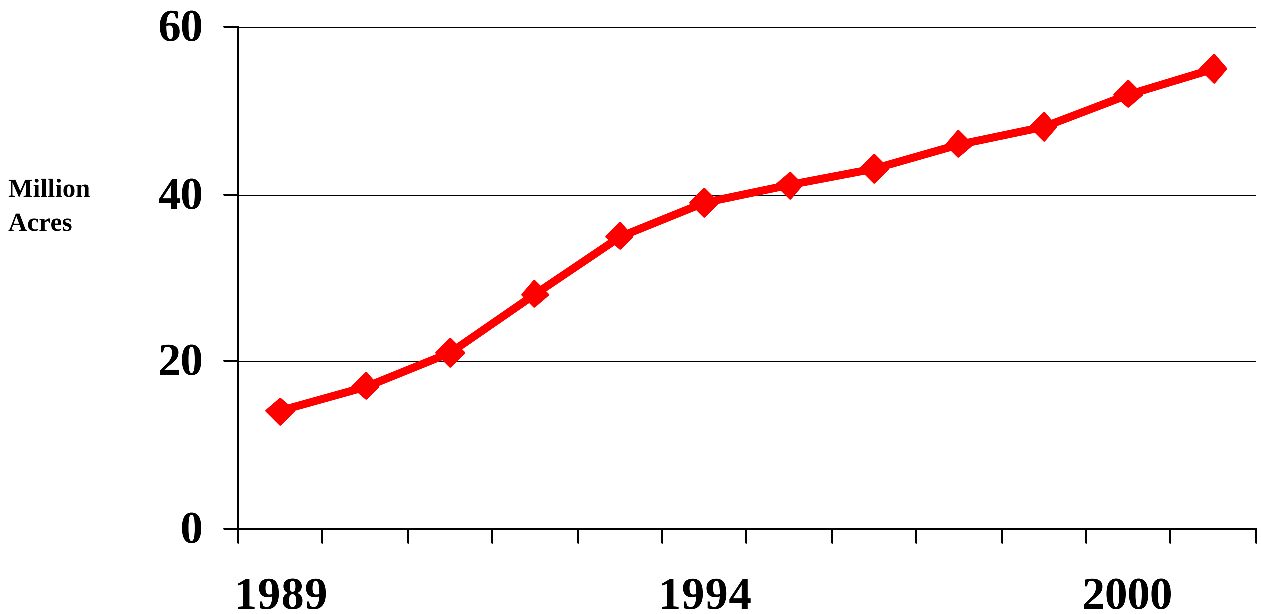
Source: [280] [390][391]

Figure A 34: U.S. Organic Cropland Acreage



Source: [305]

Figure A 35: U.S. No-Till Acreage



Source: [72]

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