Hoes to Herbicides:

Economics of Evolving Weed Management in the United States

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Abstract: *Over the past century, U.S. field crop farmers have controlled weeds with progressively less costly technologies, moving from hoeing and draft cultivation to motorized cultivation to selective herbicides to broad-spectrum herbicides associated with herbicide-tolerant (HT) crops. The advent of herbicides had the effect of reducing both capital and labor costs by reducing the number of field passes required for effective motorized weed control. The advent of HT crops again reduced both labor and capital costs. These innovations have attracted widespread adoption by farmers. Today, HT crops and broad-spectrum weed control are used by virtually all field crop farmers except those producing for markets that will not accept genetically modified crops. The accelerating spread of herbicide-resistant crops (an adaptive evolutionary response to extensive reliance on a few herbicides) is triggering U.S. farmers to increase and diversify their herbicide use, increasing both financial costs and selected health and environmental risks.*

Keywords*: weed control, herbicide, genetic modification, herbicide-tolerant crop, technological change, labor-saving, agricultural innovation.*

Herbicides are the dominant weed control method for U.S. agriculture. But it was not always thus. Over the past century, weed management in the United States has evolved with changing crops, rural-to-urban migration, and three waves of technological change. Today, three distinct approaches to weed control coexist in contemporary U.S. weed management, including two that rely on herbicides and one that does not. How we got to where we are is a tale that begins with how weeds do damage and proceeds with the history of the past century of weed technology development and associated farmer adoption in the United States. To answer why U.S. weed management evolved as it has, the article taps an economic conceptual model of how farmers choose weed control methods and uses that model to examine current market and weed conditions that result in the trifurcation of current weed control strategies. The article closes by discussing future prospects for agricultural weed management in the United States in light of the challenges of evolving weed resistance to herbicides.

Weeds and weed control

A weed is a plant growing where it is not wanted. Agriculturally, weeds compete with crops for sunlight, water, and nutrients (Hay, 1974). In so doing, they damage crop productivity by reducing yield quantity, quality, or both. Weeds differ from other agricultural pests in two important ways. First, weeds damage crops indirectly by competing for resources, whereas insects, fungi, and diseases damage the crop directly. Second, weeds do not move within a growing season, unlike insects, birds, rodents, fungi, and diseases that can move between fields and arrive at any point during a growing season.

Annual weeds emerge from where their seeds lie, and seeds can persist in the soil for many years. Once established, perennial weeds may persist for many years. These two factors, combined with the widespread dispersal of weed seeds by wind, water, and human movement, make difficult the complete removal of weeds.

Weed control is typically done either by preventing weed seeds from sprouting or by killing the sprouted weeds before they can damage the crop. Deep burial via plowing is one method to prevent seed sprouting, at least in the near term. Killing weeds can be done by uprooting, severing, poisoning (with herbicide), or outcompeting them (as with a healthy, overshadowing crop). Weed control methods can be broadly grouped into four categories: (i) manual, (ii) mechanical, (iii) chemical, and (iv) genetic plus chemical methods. These methods and their evolution are described below.

Manual weed control methods have been practiced since the beginning of agriculture (Hay, 1974; Timmons, 2005). They involve physically removing weeds, severing them, or burying them so that they are deprived of sunlight. Laborers with hand hoes or leading draft animals dragging light field cultivators will pass over fields turning the soil to uproot established weeds or bury seeds to deter germination.

Motorized mechanical weed control uses largely the same physical methods as manual weed control, but tractor-power enables it to cover ground much faster, including with enhanced practices like rotary-hoeing. Because weeds emerge at different times, both manual and mechanical weed control require that fields be weeded repeatedly during a crop season, both before and after crop emergence.

Modern chemical weed control methods became widely available in the 1950s following advances in chemical science following the Second World War (Hay, 1974; Timmons, 2005; Vats, 2015). Herbicides can be applied rapidly via self-propelled or tractor-drawn broadcast sprayers or alongside field cultivation through banded spraying. Multiple chemicals can be applied, and some herbicides remain effective in the soil for many weeks.

Herbicides can be applied before and/or after crop emergence, depending on the formulation. Pre- plant herbicides are incorporated into the soil before the crop is seeded, preventing seeds from germinating or killing weed seedlings as they elongate through the treated layer of soil. Pre-emergence herbicides are applied to the soil surface without incorporation before or after crop seeding. They damage weeds that have already germinated but have yet to emerge. Post-emergence herbicides are effective against weeds that have already emerged from the soil (Vats, 2015). Figure 1 illustrates the time intervals over which different weed control methods may be used, including manual, motorized, and pre-plant, pre-emergence, and post-emergence herbicides.

Herbicides are organized into over a dozen site of action (SOA) categories, and they poison weeds in various ways. The major biochemical modes of action by which herbicides kill plants include inhibiting photosynthesis, respiration, cell division and tissue growth, seedling growth, lipid synthesis, nitrogen metabolism, synthesis, and enzyme activity (Anderson, 1983)[1]. Some herbicides (e.g. 2,4-D and glyphosate) are active only when absorbed directly by a growing plant; hence, they must be applied post weed emergence. Others (e.g., trifluralin) are effective on the development of germinating seedlings, so they must be applied to the soil before weed germination. Similarly, some herbicide modes of action are effective only in certain families of plants (e.g., broadleaf) but not others (e.g., grass). One such herbicide is 2,4-D, which is toxic to broadleaf plants, so can be applied to kill broadleaf weeds in grass crops like corn or wheat without damaging the crop.

Just as motorized power extended the reach of manual weed control practices, so too the advent of herbicide-tolerant (HT) crops has extended the reach of certain broad-spectrum herbicides. For example, Roundup-Ready™ crops can tolerate exposure to glyphosate (Roundup™), while Liberty Link™ crops tolerate exposure to glufosinate. HT crops enable growers to replace selectively targeted post-emergence herbicides with ones providing broad-spectrum weed control. However, the popularity of HT crops in many developed countries has led to development of herbicide resistance among weeds to the associated herbicides; in effect, weeds have evolved

[1] Updated from United Soybean Board, "Herbicide Classification" chart, http://takeactiononweeds.com/wp-content/uploads/herbicide-classification-chart_2016.pdf (downloaded July 22, 2016).

parallel genetic herbicide tolerance to what was genetically engineered for crops. As resistant weeds spread, the advantages of HT crops shrink, as discussed later.

History of technological change in U.S. weed control

Today's agricultural weed management technologies evolved through three waves of technological change. The waves can be seen as a process of saving labor. Weed control tends to be a highly labor intensive process. Each new technological wave has allowed growers to reduce labor inputs further (Hay, 1974).

In first half of the 20th century, U.S. farmers controlled weeds manually. Through the 1930's, weed control by hand hoeing and draft-powered cultivation remained unchanged from centuries past. While manual weed control is scarcely used today in field crop operations in the United States, it remains practiced for selected horticultural crops. Vegetable and berry crops, which have far fewer approved herbicides than field crops, continue to utilize crews of laborers to hand hoe and weed fields as standard practice (Baker, 2015).

Although gasoline-fueled tractors appeared in the United States by 1910, early tractors were capable of plowing and threshing only (Cochran, 1993; Williams, 1987). Only after the development and diffusion of tractors with high axle clearance and rubber tires by the late 1930's did it became possible to do in-row cultivation to eliminate weeds while the crop was growing (Sahal, 1981). Not until 1947 did hydraulic remote control, continuous running power take-offs, and the three-point hitch make possible effective tractor-powered weed control. Over the next 20 years, U.S. tractor ownership quadrupled to 4 million (while horse and mule numbers dropped by three-quarters) (Williams, 1987). Motorized mechanical weed control technologies have evolved from row cultivators to rotary hoes for rapid control of emerging weed seedlings with minimal crop damage. Mechanical weed control using cultivators and rotary hoes remains the dominant form of weed control for organic farmers in the United States.

The year 1947 also saw the introduction of 2,4-D, the first widely adopted herbicide for field crops. Applied to growing plants, this post-emergence phenoxy compound inhibits the growth of broadleaf weeds (Hay, 1974; Vats, 2015). The triazine family of herbicides followed soon after, including atrazine in 1958. Triazines work by inhibiting photosynthesis when applied pre-emergence or early post-emergence (Timmons, 2005; Vats, 2015); they have efficacy on broadleaf plants and selective efficacy on grasses (Anderson, 1983). Both these classes of herbicide could be used on corn, with major labor savings (and likely also yield gains). The 1960's saw weed management in U.S. corn production transformed. Between 1957 and 1971, herbicide use soared from 27% to 79% of U.S. corn land (Figure 2). Amides, anilines, and carbamates represented the next phase of herbicide development during the 1960's. These pre-emergence herbicides work by inhibiting seed germination (Vats, 2015), making them viable for use on broadleaf crops. As a result, between 1966 and 1976, the U.S. soybean acreage treated with herbicides followed that of corn, jumping from 27% to 88% in a decade (Figure 2).

By 1982, herbicides had become the norm for weed control in U.S. field crops, where they were used on 93% of soybean and 95% of corn acreage (Figure 2). Over the previous 20 years, U.S. farmers had first experimented with herbicides to supplement tillage for weed control. They rapidly came to rely on herbicides, typically applying them twice, once before and once after the crop emerged. Cultivation became a supplementary weed control activity, instead of the primary one.

The next step in the evolution of U.S. weed management was triggered by a new class of broad spectrum herbicides, the phosphinics (including both glyphosate and glufosinate) (Appleby, 2005; Vats, 2015). Introduced in the 1970's, these compounds operate by inhibiting the ability of plants to synthesize and metabolize amino acids when applied to the weed post-emergence. Because they block an important enzyme production pathway, they are lethal to most plants. Their broad spectrum plant toxicity enabled them to be used in lieu of tillage to kill weeds before planting. Early use of phosphinics facilitated no-till planting in the 1970's and 1980's, a conservation practice that promised to reduce soil erosion (Fernandez-Cornejo, Hallahan, Nehring, Wechsler, & Grube, 2013).

The commercial introduction of glyphosate-tolerant soybeans under Monsanto's Roundup Ready brand in 1996 ushered in a new era of weed control in row crops. HT varieties of corn, as well as cotton and canola, were introduced soon after (Dill, 2005). The introduction of glyphosate-tolerance allowed farmers to rely on a single chemical, applied only after crop emergence. The rationale for adopting no-till farming shifted from soil conservation to labor saving. Between 1996 and 2006, HT soybeans went from 7% to 89% of U.S. soybean acreage, while between 2001 and 2014, HT corn went from 8% to 89% of U.S. corn acreage (Figure 2).

The introduction of HT crops transformed herbicide markets along with crop management. In 1982, when U.S. herbicide volume reached its peak, the five early herbicide groups—phenoxys, triazines, amides, anilines, and carbamates—accounted for 89% of the total (Figure 3). Relative shares remained stable in the face of reduced crop area and herbicide sales through the mid 1990's. By 2010, however, the phosphinics accounted for 55% of the total (up from just 4% in 1995). That period saw a rash of mergers and acquisitions whereby chemical companies took over seed companies to form "life sciences" companies. Among the most prominent moves were Monsanto acquiring Dekalb Genetics in 1995 and Cargill's international seed division in 1998, alongside Dupont's purchase of Pioneer Hi-Bred in 1997 (Howard, 2009). The upshot was a dramatic concentration of market power. Between 1980 and 2005, the number of herbicide companies in the United States shrank from 29 to 8 (Appleby, 2005). A new round of mergers and acquisitions in the biotech seed and associated chemical industries threatens to concentrate the market power even more (Maisashvili et al., 2016).

The pattern of herbicide adoption observed by U.S. field crop farmers—including the reasons that adoption of herbicides remains less than 100%--can be explained with the aid of a conceptual model of weed control and how the availability of herbicides affects the demand for labor and capital inputs.

Cost minimization model of weed control

As herbicides are a damage control input (Lichtenberg & Zilberman, 1986), we specify crop yield, *y*, in two arguments. The first argument is weed-free potential yield, y^0, which is a function of yield- increasing inputs labor (L^0), capital (K^0), and variable inputs unrelated to weed control (x^0):

$$y^0 = y^0(L^0, K^0, x^0)$$

The second argument in the yield function is weeds (*w*) that reduce yield convexly (y'(*w*)<0; y"(w)<0), but which can be controlled by labor (*L*), capital (*K*), and herbicide (*h*) inputs (also with convex effects)[2], so embedding y^0 into the full equation, yield is expressed as:

$$y = y(y^0, w(L, K, h))$$

Given this yield function, the farmer's problem is to minimize costs, subject to protecting crop yield, *y*, so it exceeds the minimum acceptable yield, $\bar{y}$[3]. Inputs are not separable, as herbicide application requires labor and capital, although mechanical weed control can replace herbicides by labor and machinery. Herbicides are a family of varied chemicals that are typically applied at a prescribed dose, like medicines and other pesticides. Hence, in modeling *h* analytically as a variable input, our chief interest is to illustrate input substitution, rather than to present a model of herbicide selection. Because

[2] We assume that herbicides have constant efficacy in controlling weeds. This assumption is consistent with farmers' historic perception of herbicidal weed control. It also fits with recent survey evidence that many U.S. farmers are optimistic that technological change can maintain weed control efficacy in the face of evolving weed resistance to certain herbicides (Dentzman, Gunderson, & Jussaume, 2016).

[3] In addition to weed-free yield and weed infestation in a given year, a farmer may base the desired level of weed control upon dynamic considerations that account for how weed control in one season can reduce weed seed contributions to the soil seed bank (Swinton & King, 1994). While a dynamic individual perspective would add inter-temporal risk preferences to the model, the optimality conditions for risk neutral or risk averse farmers would retain the same structure. The likely outcome in a dynamic model would be a lower weed density threshold for weed control due to the higher marginal value of herbicidal weed control and the higher averted marginal cost of labor and capital. A worthwhile future extension of the model here would be one with declining expectation of future herbicide efficacy; such a model does not describe current farmer expectations, but may do so in the near future.

herbicides can substitute for both labor and tillage in weed control, let *L(h)* and *K(h)* be functions that are decreasing in *h*. We assume that weed control and other inputs, x, are independent of one another, consistent with the idea of weed control inputs as damage control agents. Let the cost function, *C(.)*, be linear in exogenously determined prices for labor (p^L), capital (p^K), herbicides (p^h), plus the fixed cost (*FC*) of producing weed-free yield, y^0.

$$\min_h C(L, K, h) = p^L L + p^K K + p^h h + FC$$

$$s.t. \quad y(y^0, w(L(h), K(h), h)) \geq \bar{y}$$

Differentiating of the associated Lagrangean function, optimal herbicide use level must meet the following conditions:

$$p^h = \lambda \left(\frac{\partial y}{\partial w} \frac{\partial w}{\partial h} + \frac{\partial y}{\partial w} \frac{\partial w}{\partial L} \frac{\partial L}{\partial h} + \frac{\partial y}{\partial w} \frac{\partial w}{\partial K} \frac{\partial K}{\partial h} \right)$$

$$p^L = \lambda \left(\frac{\partial y}{\partial w} \frac{\partial w}{\partial L} \right)$$

$$p^K = \lambda \left(\frac{\partial y}{\partial w} \frac{\partial w}{\partial K} \right)$$

Interpreting λ as the shadow crop price (*p*), the last two conditions can be substituted into the first one to yield:

$$p^h = p \left(\frac{\partial y}{\partial w} \frac{\partial w}{\partial h} \right) + p^L \frac{\partial L}{\partial h} + p^K \frac{\partial K}{\partial h} \tag{1}$$

The optimality rule in Eq. (1) shows that cost-minimizing herbicide use has two components. The first component is the familiar result that a herbicide should be used up to the point where its cost equals the marginal value product of the yield protection it provides (the first term of the right-hand side). The second component captures the effect of herbicide use on labor and capital inputs (last two terms on the right-hand side). It says that herbicides provide supplemental value by reducing the marginal input cost of labor and capital that would be used for weed control. By capturing this effect of herbicides as a partial substitute for labor and capital in production, Equation (1) adjusts the classic single-input MVP rule by the marginal cost reduction effects of herbicide use on labor and capital requirements. The upshot is to imply that optimal herbicide use is higher (and labor and capital use are lower) than would prevail if herbicides could not substitute for labor and capital in controlling weeds. The potential for substitution begs the empirical questions,

1. At what rate do labor and capital substitute for one another under different weed control technologies?
2. How do the relative prices of labor and capital affect the preferred weed control technology?

Representative cost analysis of contemporary weed control

A simple approach to answering these questions empirically draws upon cost of production budgets for currently available alternative technologies that attain comparable levels of weed control with different input mixes. We have conducted a cost analysis of three weed control methods currently used in the United States. Each method aims for near perfect weed control of corn on a representative 1,000-acre Midwestern farm growing corn and soybean. The weed control practices associated with each come from Christy Sprague[4], a Michigan State University weed scientist. The three regimes recommended were:

1. Mechanical, with no chemicals used. This regime includes two field passes with a field cultivator prior to planting, three passes with a rotary hoe after planting, and two additional passes with a row cultivator.
2. Chemical, in which pre- and post-emergence herbicides are used without requiring an HT crop. This scenario is relevant either when a genetically modified crop is unacceptable to the grain buyer or when herbicide-resistant weeds require mixed herbicides for effective weed control. In this case, a pre-plant pass with a field cultivator is supplemented by a pre-emergence application of a mix of herbicides using a broadcast sprayer. After crop emergence, another broadcast application of a selective herbicide (such as glyphosate with HT seed or 2,4-D otherwise) is used.
3. Genetic + chemical, in which the genetic properties of the seed allow for reliance on a single broad-spectrum herbicide such as glyphosate or glufosinate. In this case, a single pass with a field cultivator

[4] Christy Sprague, Professor, Dept. of Plant, Soil and Microbial Sciences, Michigan State University. Personal communication by personal interview with Braeden Van Deynze and Scott Swinton, Plant and Soil Sciences Building, Room 466, East Lansing, MI, Oct. 4, 2016.

pre-plant is followed by a single broadcast application of a broad-spectrum herbicide after the crop has already emerged.

Annual weed control costs per acre at 2015 prices were calculated for each of these scenarios. Labor, machinery, and fuel costs were estimated using the University of Minnesota farm machinery cost estimate tool, applying the default global variables such as wage rates, fuel prices, interest rates, insurance costs, and inflation (Lazarus, 2015). Chemical prices were based on observed prices paid by Michigan farmers by C. Sprague (2016, personal communication), with application rates assumed to follow those specified on the herbicide label. Due to the prevalence of HT seed in corn crops, all three scenarios used HT seed, so there is no difference in licensing costs and seed cost dropped out of the analysis. Costs were partitioned into labor time (measured in hours per acre-year) and capital costs (measured in dollars per acre-year). Capital costs include all machinery, fuel, and chemical costs. Table 2 disaggregates capital costs into mechanical and chemical components, while Figure 4 combines them, presenting each technology scenario as a point in labor-capital space.

The striking feature of Figure 4 is that the Genetic + Chemical treatment cost-dominates both of the other treatments, requiring less labor and less capital expenditure than either of the other two weed control technologies. Labor and capital are used in fixed proportions under this technology, so, in answer to the first research question, the marginal rate of substitution between these inputs is nil. Crop farmers who cannot use that technology (perhaps due to herbicide resistant weeds) face trade-offs between the other two. Chemical Only weed control demands more capital, but less labor than the Mechanical weed control. The marginal rate of input substitution (slope of the isoquant segment) between Mechanical and Chemical Only technologies is -0.054 hours/dollar capital, implying that Chemical Only is lower cost when wages exceed roughly $19/hour, but Mechanical is cheaper at lower wages. At prevailing assumptions about the cost of U.S. farm skilled labor at $25/hour (Lazarus, 2015), Chemical Only would be the cost-minimizing option of the two. Of course, regardless of relative input prices, organic farmers, who may not use chemical or genetically modified technologies, will prefer the Mechanical system. Because of how the Genetic + Chemical weed control technology nests the other two, the answer to the second research question is that the relative prices of labor and capital matter only if the grower is constrained not to use this technology. The cost minimizing nature of this technology explains its rapid rate of adoption.

Evolution of labor and capital use for weed control in corn

While the isoquants in Figure 4 represent modern weed control options, they can also be viewed as representing the progression of weed control technologies through time. The dominant weed control regime prior to the rise of herbicides in the 1950s and 1960s was a version of the Mechanical regime presented here, albeit with far less efficient tractors and implements (Hoy et al., 2014). With the advent of commercial herbicides, the Chemical regime became available to farmers; later the Pareto superior Genetic + Chemical regime also became available. Through this historical lens, the cost effectiveness of each regime is a clear explanation of the sequential pattern of adoption of both herbicides and herbicide-tolerant crops by U.S. crop farmers (Figure 2).

How herbicides drove down labor use for weed control is illustrated in corn cost of production data recorded by University of California-Davis extension scientists during 1954-2015 (Figure 5). Despite the uniqueness of much California agriculture, the pattern of weed control practices in Sacramento Valley corn is indicative of management elsewhere in the United States. Until 1963, weed control relied on 1 to 1.2 hours per acre (h/ac) of mechanical cultivation. Introduction of 2,4-D for chemical weed control in 1963 causing the time spent on mechanical cultivation to drop by half immediately to 0.6 h/ac and to continue dropping to 0.33 h/ac in 1967 and 0.2 from 1987 onward. Total labor use for weed control fell by two-thirds, from 1.0-1.2 h/ac to 0.3-0.4h/ac. The upper end of this labor band represented years with pre-emergence weed control, which typically increased yields. By 2000, Sacramento Valley corn growers had dropped pre-plant herbicides, as HT corn allowed reliance on post-emergence weed control with glyphosate and 2,4-D, bringing total labor use for weed control to under 0.334 h/ac (Figure 5).

Reduced labor demand for weed control freed up labor for other purposes, including larger farms. As with the case of mechanization, it is not clear whether reduced labor use was cause or consequence of adopting the new technology (Kislev & Peterson, 1986). What is evident is that the size of commercial field crop farms grew notably following the introduction of herbicides. From 1900 through 1950, the mean American farm size grew by half, from 150 to 225 acres. During the 1950's, following the introduction of herbicides, the mean American farm size jumped by 44% to 325 acres. By 2000, the mean American farm had reached a size of 475 acres, representing 210% growth during the second half of the century, compared to 50% growth during the half before the advent of herbicides (Eastwood, Lipton, & Newell, 2010). While causality is unclear, the introduction of herbicides correlates strongly with a dramatic change in the scale of American farm operations.

Herbicides, human health and environmental quality

Herbicides in the United States have had mixed effects on human health and the quality of the environmental in rural areas. The environmental effects on soil conservation have been clear and beneficial, while those on monarch butterflies have been harmful (Pleasants & Oberhauser, 2013). Effects on human health is less clear, due to the diversity of herbicide chemistries, the difficulty of measuring chronic health effects of herbicides, and the scarcity of comparisons with health effects of non-herbicidal weed management.

The introduction of glyphosate and glufosinate in the 1970's set the stage for no-till farming, which has generated important soil conservation benefits. These new herbicides could be applied before crop planting to "burn down" weeds in a field. Because they absorbed through leaves, they would do no harm to crops planted afterward. But the adoption of no-till and conservation tillage accelerated after the introduction of HT crop varieties. According to a 1997 USDA survey, 60 percent of U.S. land planted under HT soybeans also used conservation tillage, compared to only 40 percent of land planted under conventional soybeans (Fernandez-Cornejo & Caswell, 2006). Although the literature is divided as to the direction of causality between adoption of HT crops and of conservation tillage, analysis of USDA surveys over 12 states during 1996-2006 finds that a 10 percent increase in HT soybean adoption leads to a 2.1 percent increase in conservation tillage (Fernandez-Cornejo et al., 2013). These results, based on Granger causality tests, suggest that the adoption of HT crops for weed control triggers increased soil conservation.

The highly efficacious, broad-spectrum weed control of glyphosate and glufosinate have been implicated in the dramatic decline of the monarch butterfly in eastern North America. Monarch butterflies migrate from winter habitat in the highlands of south-central Mexico to summer habitat east of the Rocky Mountains in the United States and southern Canada. Monarch populations have been in decline for over 15 years. The butterflies feed chiefly on milkweed, the abundance of which has dropped sharply with the expansion of glyphosate and glufosinate herbicide use in Midwestern agriculture (Pleasants & Oberhauser, 2013; Flockhart, Pichancourt, Norris, & Martin, 2015)(Flockhart, Pichancourt, Norris, & Martin, 2015).

Measuring the human health effects of herbicide technology is complicated. As a class of plant toxins, herbicides are generally much less toxic to humans than insecticides and fungicides. Nonetheless, they are by far the most heavily applied pesticide class in U.S. agriculture (Fernandez-Cornejo et al., 2014), and they can have varied effects, depending on dose, timing, environmental fate, and form of human exposure (Shogren, 1990). In general, pesticide risks are far greater to farm workers who apply them than to consumers (Harper & Zilberman, 1992). To our knowledge, there has been no careful study of how the farmer health effects of herbicides compare to the health effects of the hard labor associated with weed control (while holding constant crop output).

Most available data cover acute human health risks, rather than chronic ones. The early expansion of glyphosate use on HT crops in the United States reduced acute health risks (Bonny, 2016), as glyphosate replaced more toxic herbicides. Glyphosate, now the leading herbicide used in the United States, is ten times less toxic than 2,4-D and to one hundred time less toxic than trifluralin, as measured by the dose that would be lethal to 50% of a population of laboratory mice (LD50) (Fernandez-Cornejo et al., 2013). Evidence of chronic health risks from herbicides is scarcer, though several studies explore the carcinogenicity of glyphosate. A recent review by the U.S. National Academy of Sciences concludes that, “a major government-sponsored prospective study of farm-worker health in the United States does not show any significant increases in cancer or other health problems that are due to use of glyphosate” (National Research Council (NRC), 2016) (p. 154). However, the broader human health effects of herbicides are threatened by increased use triggered by herbicide-resistant weeds (see below).

Herbicide-resistant weeds, management responses, and associated effects

The most recent stage in the evolution of weed management in U.S. field crops is currently unfolding with responses to herbicide resistant weeds. The problem is not new. The first herbicide resistant weed was recorded sixty years ago in 1957[5]. Thirty years ago, economists characterized pesticide resistance as a public good problem that tempted farmers to overexploit the open access resource of pest susceptibility to a pesticide (Miranowski & Carlson, 1986). At the time, the mobility of insect pests seemed to make insects more vulnerable than weeds to depletion of the stock of pesticide susceptibility. There is now substantial evidence that the wind carries herbicide-resistant weed genes as pollen and seeds, making weeds too highly vulnerable to the development of genetic resistance. Likewise, evidence exists that farmers increasing perceive weed resistance as a common pool resource problem (Hurley & Frisvold, 2016). For both insects and weeds, the problem is exacerbated by the overreliance on a few pesticides that has accompanied the advent of genetically modified crops (Bonny, 2016; Mortensen, Egan, Maxwell, Ryan, & Smith, 2012). Indeed, the short-run, cost minimization model of farmer behavior captured in Equation (1) would predict heavy reliance on herbicides due to the private benefits they provide.

Widespread reliance on just two broad spectrum herbicides—glyphosate and glufosinate—has led to a proliferation of weed species with varying levels of tolerance of these herbicides. That, in turn, has prompted a variety of weed management responses (Livingston et al., 2015), foremost among them increased application of herbicides in general, including a more diverse mix (Bonny, 2016). To a substantial extent, the challenge of controlling herbicide-resistant weeds is inducing farmers to return to a second herbicide pass and hence to increase labor and equipment use, as under the Chemical

[5] Spreading Dayflower resistant to 2,4-D in Hawaiian sugarcane was recorded in 1957 (International Survey of Herbicide Resistant Weeds database at http://weedscience.org/details/case.aspx?ResistID=394, accessed Aug. 18, 2016.)

technology scenario in Figure 4 (C. Sprague [2016], personal communication). A side effect of herbicide resistance is that the use of more herbicides overall and the return to use of toxic ones is likely also increasing human health hazards.

Conclusion

Over the past century, U.S. field crop farmers have controlled weeds with progressively less costly technologies, moving from hoeing and draft cultivation to motorized cultivation to selective herbicides to broad-spectrum herbicides associated with herbicide-tolerant (HT) crops. The advent of herbicides had the effect of reducing both capital and labor costs by reducing the number of field passes required for effective motorized weed control. The advent of HT crops again reduced both labor and capital costs. These innovations were greeted with widespread adoption by farmers. Today, virtually all field crop farmers use HT crops and broad-spectrum weed control, except those producing for markets that will not accept genetically modified crops. The accelerating spread of herbicide-resistant crops (an adaptive evolutionary response to extensive reliance on a few herbicides) is triggering U.S. farmers to increase and diversify their herbicide use, increasing both financial costs and selected health and environmental risks.

The spread of herbicide resistant weeds is the single, most urgent challenge to agricultural weed management in the United States. The chemical industry is responding with the development of new crop varieties that include stacked HT genes that add to glyphosate tolerance the ability of crops to withstand other herbicides, such as 2,4-D and dicamba (Bonny, 2016). Information-based strategies, such as integrated weed management, are returning to prominence after a period when the prophylactic weed control associated with HT crops seemed to obviate the value of scouting weed populations and tailoring management responses (Mortensen et al., 2012). Advances in proximate sensing and weed recognition technologies are lowering the cost of integrated weed management, though it is not clear that costs can come down (or the revenues from non-HT varieties rise) sufficiently for site-specific weed management to become commercially attractive in commodity crops (Swinton, 2005). While information-based management approaches by individual farmers may be necessary for slowing the advance of herbicide resistance, it is not clear that they will be sufficient to meet the challenge. Emerging research explores collective weed management approaches that are tailored to the common pool resource problem and associated transaction costs (Frisvold & Ervin, 2016).

Table 1: Schematic eras for weed control technology

Management method	Labor	Fixed Capital	Variable Capital	Dominant Era
Manual	Very High	Low	Very Low	1600's – 1930's
Mechanical	Medium	High	Medium	1930's – 1960's
Chemical	Low	High	Medium	1960's – Present
Genetic & chemical	Very Low	High	Medium	2000's – Present

Table 2: Components of annual labor and capital costs per acre for three weed control technologies on a representative 1000-acre Midwestern U.S. corn-soybean farm in 2015.

Method	Description (including boom width)	Labor time (hours/acre)	Mechanical capital costs (US$/acre)	Chemical capital costs (US$/acre)
Mechanical	2 field cultivator passes (47 ft) 3 rotary hoe passes (30 ft) 2 row cultivator passes (30 ft)	6.65 hours	$56.11	N/A
Chemical	1 field cultivator pass (47 ft) 1 pre-plant broadcast spray (s-metolachlor and atrazine) 1 post-emergence broadcast spray (glyphosate, atrazine, and mesotrione)	1.96 hours	$10.96	$47.75
Genetic + Chemical	1 field cultivator pass (47 ft) 1 post-emergence broadcast spray (glyphosate and atrazine)	1.25 hours	$8.37	$7.63

NB: Assumes 4% interest rate, 0.85% insurance rate on machines, 2.50 USD/gallon fuel costs, no inflation.

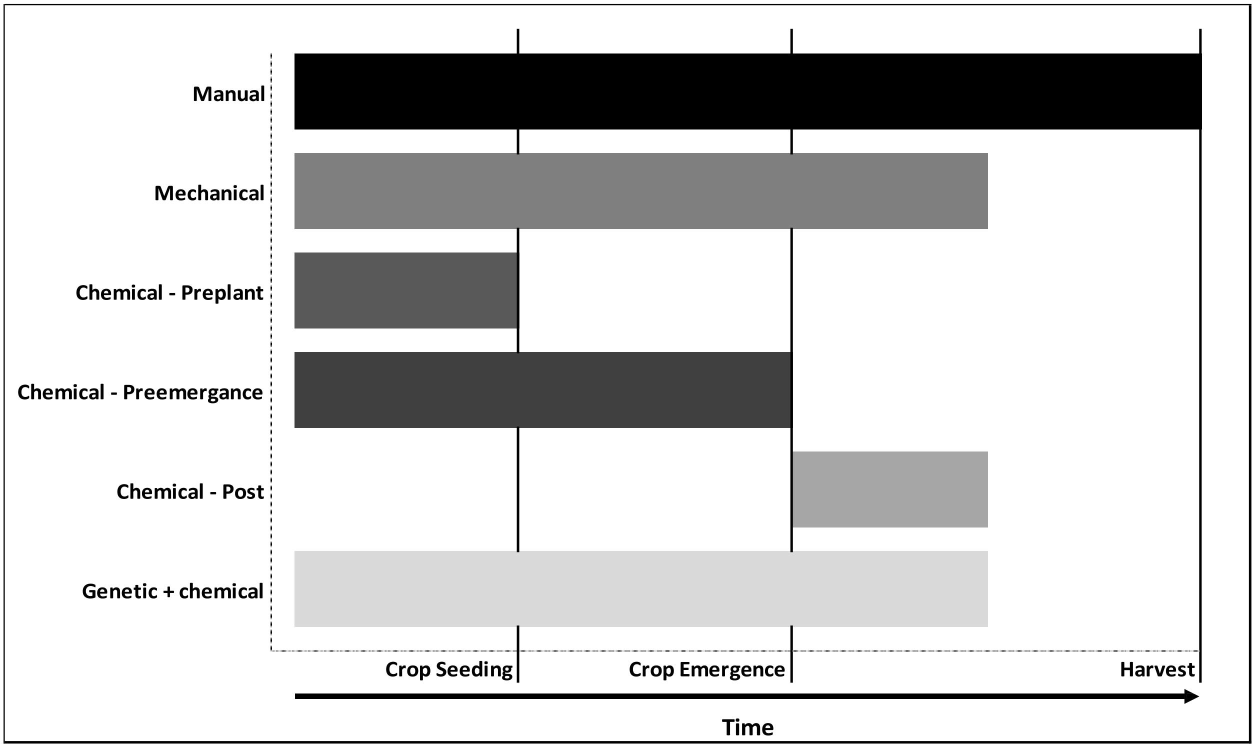

Figure 1: Feasible timing intervals for alternative weed control practices.

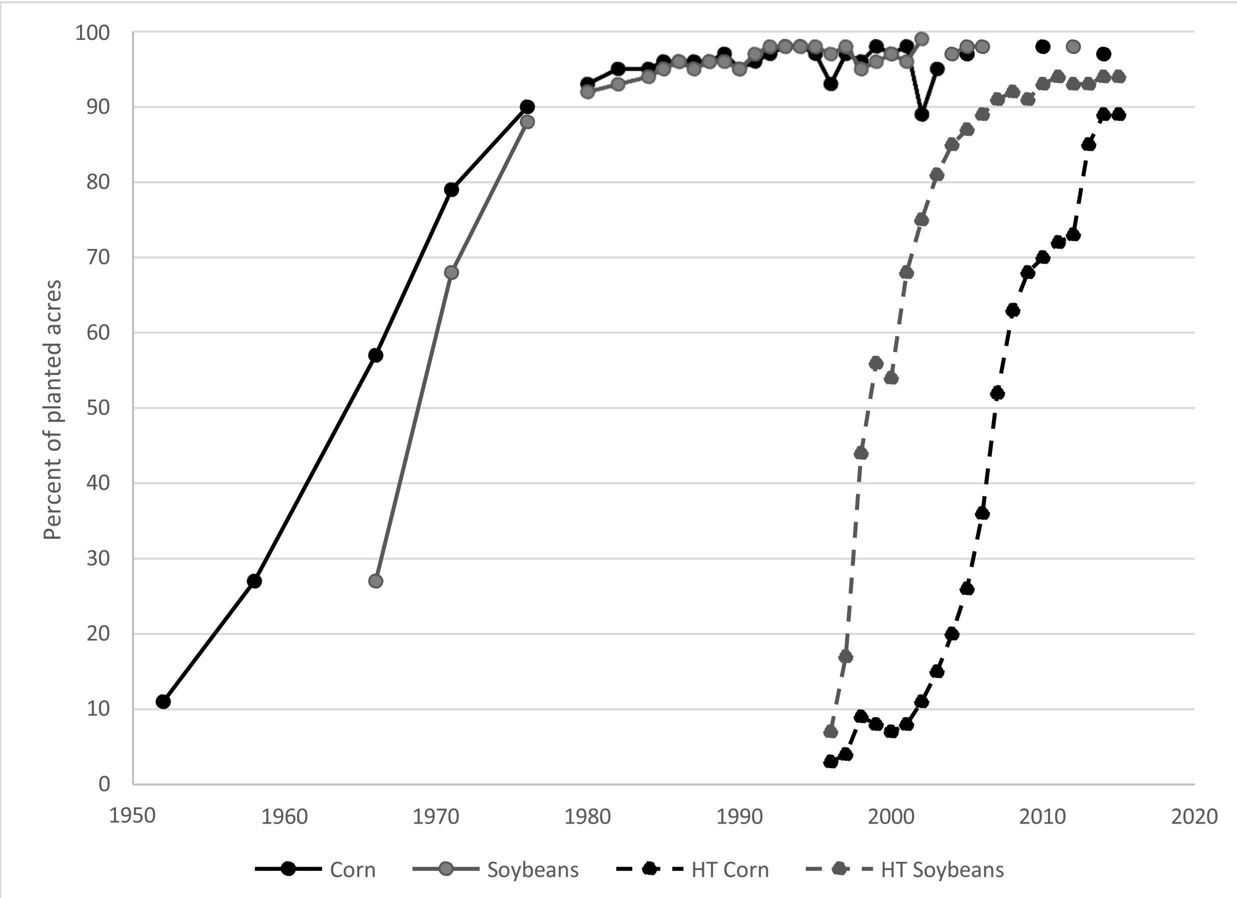

Figure 2: Percent of U.S. planted acres of corn and soybean treated with herbicides and genetically-engineered, herbicide-tolerant (HT) varieties, 1952 – 2015. Sources: (Osteen & Fernandez-Cornejo, 2013), updated from USDA Economic Research Service (2016) http://www.ers.usda.gov/data-products/adoption-of-genetically-engineered-crops-in-the-us/recent-trends-in-ge-adoption.aspx.

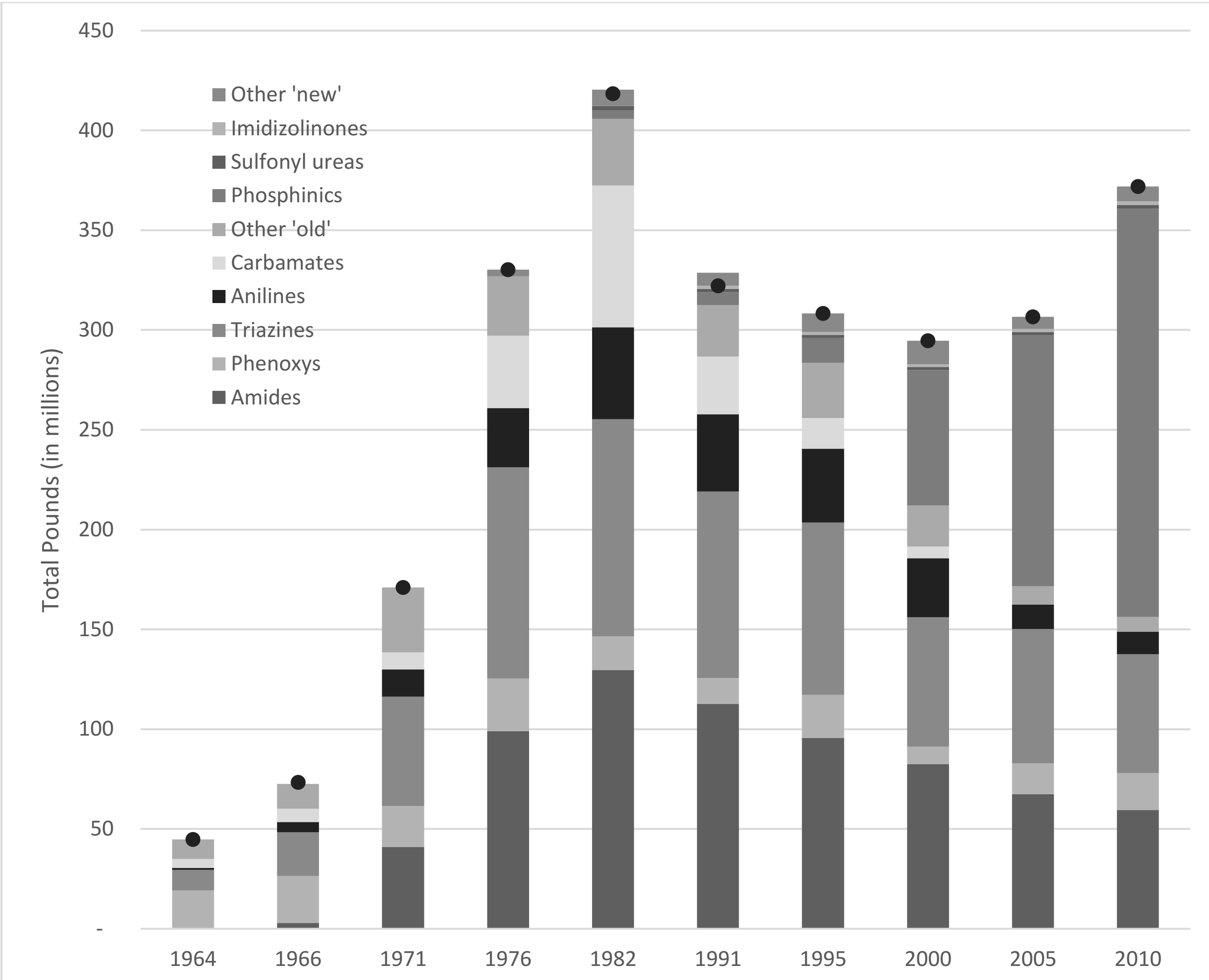

Figure 3: Total volume U.S. herbicide use by herbicide class, 1964 – 2010. Adapted from data in (Osteen & Fernandez-Cornejo, 2013) by applying herbicide class percentages to total applied volume.

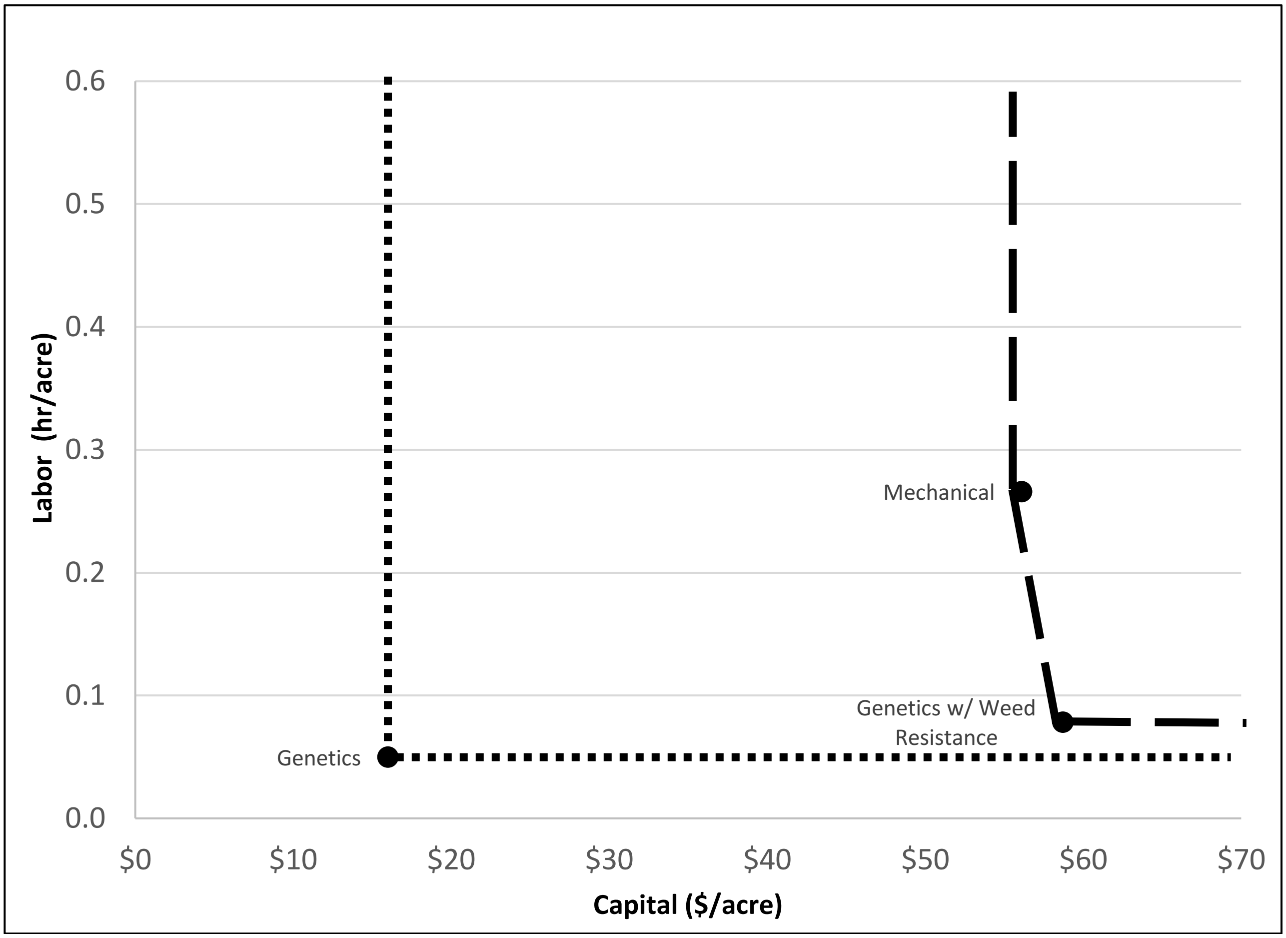

Figure 4: Labor and capital requirements for three weed control technologies, representative Midwest U.S. corn production, 2015. (Data sources: Financial from Lazarus (2015); chemical costs and amounts from personal communication with C. Sprague, professor of weed science, Michigan State University, East Lansing, MI, [interview 10/4/2016]).

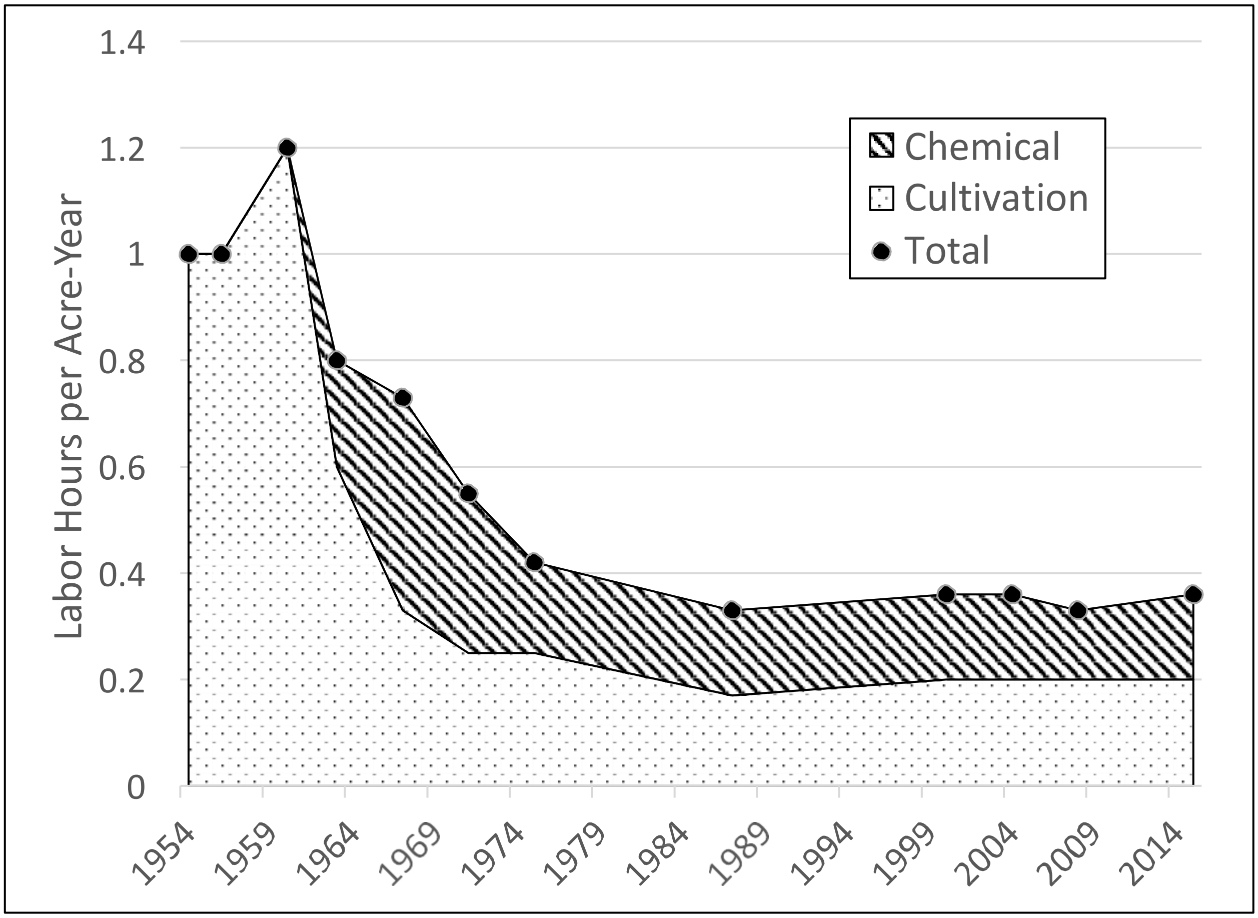

Figure 5: Labor for weed control in field corn, Sacramento Valley, California, 1954-2015. Source: ("Archived Cost and Return Studies," 2016; UC-Davis-Various-Authors, 2016)

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