NOVEL WEED MANAGEMENT: DESIGN, CONSTRUCTION, AND

EVALUATION OF TWO INTER-ROW CULTIVATION TOOLS, AND THE

INTEGRATION OF VINEGAR FOR INTRA-ROW WEED CONTROL

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Glenn Jason Evans

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NOVEL WEED MANAGEMENT: DESIGN, CONSTRUCTION, AND
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Glenn Jason Evans, Ph.D.

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Weed management is a constant agricultural concern.   Early farmers
used hand tools to control weeds. As sources of farm power shifted, with the
integration of horses, tractors, and chemicals, weed management tools and
techniques evolved in turn. Study objectives were to design, construct, and
evaluate two novel cultivators for between-row weed control; and, to integrate
vinegar, an organic herbicide, to control in-row weeds. Impetus for new
cultivator designs came from designs of antique hand-held tools. The first
tool, a block cultivator, has a flat surface which rests against the soil and limits
the entrance of a rear-mounted blade. The second tool is shaped like a stirrup
hoe with a horizontal steel blade. Block and stirrup cultivators were mounted
on a toolbar with a traditional S-tine sweep. The tri-part cultivator was tested
in 20 non-crop field events. A multivariable model was created to assess the
importance of cultivator design, and environmental and operational variables,
on post-cultivation weed survival. Cultivator design strongly influenced weed
survival (P<0.0001). The block provided significantly greater control than the
sweeps in 17 of the 20 cultivation events (P≤0.10). Of 11 environmental and
operational parameters, seven effected weed control with the sweep; five
impacted control with the stirrup, and only one influenced control with the
block. Because of the block cultivator's increased effectiveness and

operational flexibility, it has the potential to improve inter-row mechanical weed management.   A tractor mounted sprayer was constructed to direct a 25 cm band of vinegar at the base of transplanted broccoli and pepper. Organic paints were applied to crop stems and tested as potential physical barriers to crop stem injury.   A single application of 200-grain vinegar (20% acetic acid) at 700 L/ha was applied when weeds had less than six leaves. One day after application, 98% of weeds were killed. The number of germinating weeds two weeks after the vinegar application was less than a quarter of the number which had germinated at two weeks after in-row handweeding. Crop foliage was minimally injured. Neither stem paint prevented stem injury; thus, yields were reduced. More research will be needed to assess alternate stem protectants.

BIOGRAPHICAL SKETCH

Glenn is from western Pennsylvania. He had an early interest in the natural world, and extended that interest into academic pursuits. He graduated from Cornell University in 2003 with a bachelors of science. Then, he obtained a master's of science from Cornell in 2007, focusing on the weed control potential of vinegar and clove oil. Finding a sustained interest in development of new weed control alternatives, Glenn entered into a doctorate program directly following completion of his master's. His doctorate work has centered on the creation and evaluation of two new cultivators for inter-row weed control, and, the integration of vinegar to control within-row weeds.

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The Evolution of Cultivation Equipment

Introduction

Since the beginning of agriculture, over 10,000 years ago, humans have needed to cultivate the soil (Pringle 1998). There has been an ongoing evolution in tool design, and persistent changes in the power-sources used to operate cultivation implements. The general trend has been toward development of larger and more sophisticated equipment, with the aim of improving efficiencies and reducing manpower.

The source of agricultural power has been a major determining factor in the evolution of cultivation tools. Handheld implements were designed to work the soil with the limited power of an individual. With the introduction of horses into agriculture, increased amounts of soil could be moved. The subsequent entrance of steam, gasoline, and diesel-powered tractors provided even more power, in an increasing array of options. With each shift in agricultural power, so too was there a shift in the design, scale and fabrication of cultivation equipment.

What follows is an analysis of social and agricultural aspects that have contributed to the evolution of cultivation implements. On-farm power sources will be discussed with regard to their main characteristics and with reference to some of the impacts they have had on cultivation tools. The objective is to identify how key shifts in agricultural power, and in society, have fundamentally influenced the technology, availability, and capability of cultivation tools.

By Hand and By Horse

Pulling of weeds by hand and hand hoeing were the primary weed control techniques for many generations. Weed control was slow labor-

intensive work that required many individuals to tend the fields (Blandford 1976). Early hoes had a variety of different blade shapes dependent on regional preference and application (Figure 1.1). Egyptian illustrations from around 6000 B.C. showed a Y-shaped portion of a tree being used in a manner consistent to that of the present-day mattock (Gittins 1959). Artifacts dug at farmstead sites of the Jamestown colonies (founded in the early 1600's) included metal hoe heads nearly identical to the modern-day garden hoe (Cotter and Hudson 1957).

Figure 1.1. Variations in hand tools across regions and time. Clockwise; a reconstruction of a Neolithic Bali cultivation tool with a stone head; Metal tool heads found at the site of the Jamestown colonies; Zimbabwe hoes; old localized designs still in use.

An agricultural shift began as individual farmers, dependent on their own physical strength to work the fields, began to utilize horses, mules, and oxen, to carry some of their burden (John 1973). Horses were bred specifically for farming (Johnson 1976). In the Roman Empire, around 500 B.C., harrowing was done by dragging a tree branch behind slaves or cattle (Gittins 1959). This early tool was used to smooth out furrows left after rudimentary plowing or hand-digging of the soil. In time, progressive farmers put together a wooden triangular crotch with wooden teeth or iron spikes (Currie 1916). The basic principles of these early harrow designs remain prominent in modern day cultivation: spikes, tines, or sweeps are mounted beneath a support frame in an arrangement that can move soil and decrease weed competition.

Tools that evolved from hand held hoes and early harrows were basic wooden and metal frames with a single forward wheel and tines mounted onto the framework (Blandford 1976). The wheel cultivator, with steel shovels, was invented in 1848 (Gittins 1959). These cultivation units were steered with two outstretched handles, much like early plows. To hoe close to plant rows, adjustments, by way of pegs or bolts, could be made to the width of cultivation. By 1856, the straddle row cultivator appeared; these early models could cultivate the soil on each side of a single row (Timmons 1970). Names given to early cultivators included hoes, scarifiers, or scufflers (Blandford 1976). Most cultivators were shovel-types, variations of sharpened pointy-edged blades dragged through the soil. Such cultivator shovels were often little-modified from the shovels mounted on field harrows. In the 1890's, American Harrow Co. stated that they had the largest factory in the world. They marketed horse-drawn, walk behind, one-row cultivators (Wendel 2004).

Walking behind a horse-drawn plow or cultivator was a feat of endurance. To plow an acre of land required walking 10 to 12 miles, with one acre of plowing a day considered good progress (John 1973). Speaking of horse-drawn plowing, Rumeley (1910) states: "(i)t would be easier (and the distance is less) to walk around the earth at the equator (if there were no ocean) than to follow a plow turning a prairie of five square miles." The U.S. Department of Agriculture's census of farm animals in 1915 found that there were over 25 million horses and mules in use on the farm (Currie 1916). While larger farmers might have had horses enough for a job, they could not always find men to drive the horses, as farm workers were in high demand during the growing season.

Ohio Cultivator Co. was the first to make a riding cultivator (circa 1880's). Some farmers disliked the notion of sitting while cultivating. Some also argued that this type of cultivator made more work for the horse (Wendel 2004). Horse-drawn cultivators were capable tools for controlling between-row weeds, though hand-hoeing still remained necessary (John 1973).

From the 1850's onward, cultivation tools became increasingly important to equipment manufacturers and farmers alike. Around this time, thousands of United States patents were granted for cultivator variants (Wendel 2004). Manufacturers were plentiful. Many companies were small in size, producing on the order of hundreds, while several built thousands. The disk inter-row cultivator was a natural evolution from the disk harrow (Currie 1916). The spring tooth harrow and rotary hoe first came about as horse-drawn implements (Gittins 1959). Variations in cultivation equipment included: walk-behind and ride-along versions, single and multiple row configurations, and, different shovel types and mounting points (Figure 1.2).

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Figure 1.2. From top to bottom: A walk-behind single horse-drawn cultivator capable of working the soil between two rows; A ride-on two-row cultivator working in corn.

A prerequisite for the use of inter-row cultivation tools was the precise placement of crop rows with fixed spacing between rows (John 1973). Once row width became more standardized, after the advent of the seed drill, it was possible to cultivate more than one row at a time. Some early manufacturers made seed drills that could be refitted with hoes; the use of the same machine for dual purposes helped ensure that crop row spacing and cultivator spacing

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matched (Blandford 1976). With cultivation of multiple rows, it could be difficult to maintain control of a larger machine, because soil unevenness and awkward movements by the horses could shift the cultivator into crop rows. Design advancements were made which allowed the entire cultivator assembly to be moved side to side during cultivation by rear mounted handles, and later by foot-steering (Blandford 1976).

Row crop cultivators had steadily evolved from single-row walk-behind units steered with handles to one-to-three row ride-on implements steered with the feet (Johnson 1976). The passing of the horse and mule as the primary source of farm power did not occur until the early 1900's, though their use continued up through the 1950's. Emerging advances in agricultural power would shift the dynamics of horse-drawn cultivation. Small internal combustion engines became more economical than the horse. In 1910, a new engine cost about $90 per horsepower, while equal efficiency from a horse cost between $175 and 200 (Rumeley 1910).

Steam Power

A key driver in the advancing development of agricultural machines was the availability of steam power. Steam power was first integrated into agriculture in the 1840's (in the United Kingdom). The design of steam engines and tractors would remain constant for nearly 100 years (John 1973). Early designs of some machines were indirectly influenced by machinery advancements occurring in the burgeoning textile industry. For example, cast iron began to be utilized in the construction of gear wheels (John 1973). When the steam engine was mounted on wheels, steam power became a workable alternative to horse-power.

One early use of steam engines was to power the plowing of fields. Large heavy steam engines would be placed at each end of a field, and using a cable system, a plow would be pulled between the engines, back and forth, across the field (Johnson 1976). A six-furrow plow operated between two steam engines could work around 14 acres a day (John 1973). Operation of these machines was an art form. In large fields where one engine-operator was out of sight with the other, the men would communicate with whistle signals (John 1973). This idea gained attention, yet it was only in use for a short time since it was both a cumbersome and costly way to plow (Johnson 1976). Large steam tractors were also coupled directly to large 12 or 14 gang plows (Figure 1.3). Steam powered implements included plows, tined-cultivators, and harrows (John 1973).

Steam technology had several drawbacks. First, only the wealthiest farmers could afford these new machines; often, sets of machines were contracted out to work on multiple farms. Thus, many smaller farms retained their horse and plow operations. Second, steam engines were heavy and

Figure 1.3. A restored steam tractor pulling a 12-gang plow. Note that this setup required operators on the plow to raise and lower each plow share as needed.

unwieldy. An engine producing 14 net horsepower weighed 10 metric tons (24,000 lb) (John 1973). For reference, a typical riding lawnmower today produces around 20 horsepower and weighs only 225 kg (500 lb).

In the United States, the steam tractor was not extensively used until after the Civil War (1861-1865). Steam power was primarily used to run threshing equipment, sawmills, or feed grinders (Currie 1916). The high weight of these machines severely limited their use in friable soils or on hilly fields (John 1973). In addition, these tractors required water for operation, and access to water was limited in the dry Western plains. Currie (1916) wrote:

> The steam tractor was never intended for plowing. It devoured fuel like a blast furnace and possessed an unquenchable thirst. It was all to the merry if you anchored it alongside a well and a trainload of fuel, but when you tooled it out into the unwatered wastes you had to organize a reserve army to keep it fed up.

Limitations of the steam tractor facilitated a shift in interest to gas-powered tractors in the early 1900's. Nevertheless, steam power had incited a new way of thinking in agriculture, where speed and economics were highly valued. With steam power, farm tasks could be done quicker, and on a larger-scale than before.   This brand of thinking would continue to pervade agriculture, increasing the drive for further improvements in agricultural power and cultivation tools alike.

Gasoline and Diesel Power

Development of the internal combustion engine started slowly in the nineteenth century, though by 1899 there were around 100 companies building engines (Leichtle 1995). John Froehlich is credited with building the

first gasoline tractor in 1892. At first, inventors thought large; they began to design gasoline tractors for 10 and 12 gang plows (Currie 1916). The secretary of agriculture in 1915 had labeled farms as inefficient and underpowered, spurring in some ways, the push to large gas tractors (Currie 1916). Industrial promoters and farmers alike wanted large, leviathan types of tractors. The larger the tractor, the more money that could be made, and theoretically, the more work that could be done. Many of the commercially successful early tractors were simply gasoline engines mounted on a steam tractor frame (Leichtle 1995). These early machines weighed between 11 and 22 metric tons (26,000 to 50,000 lb). This was a heavy load for fledgling gasoline engines to pull, even without the additional weight of the implements being pulled.   Starting the tractors was difficult due to their large heavy engines and crude starting devices. Thousand of these tractors were sold, primarily to the large farms in the Plains.

> They were sold to effect great economies of man labor, but it soon developed that it required the services of an entire community to start one. Hundreds of farmers kept them going all night so as to be sure they would start in the morning. (Currie 1916)

Farmers, manufacturers, and distributors lost money in the large-tractor adventure. Farmers, accustomed to paying cash for items, now had to buy on credit, paying about a quarter of the cost of one of these large tractors up front. The remainder was due at the end of harvests, for the next two-to-three years. Farmers, unfamiliar with the notion of buying on credit, were beguiled into paying too much, or, with a bad harvest, forced to default on a debt. A typical tractor cost $4000, however repair bills for a single season could range

from $500 to $1500 (Currie 1916). The large gas tractors were not foolproof machines; they were complex at a time when there were not enough skilled mechanics available to maintain them. At this point, the automobile, which was the instrument by which a farmer could learn the nuances of the internal combustion engine, was not a large presence on the farm.

Lightweight tractors with small gasoline engines quickly brought about the demise of the large tractor, and provided for the first time serious competition to the steam engine. These tractors produced around 10 to 20 horsepower at the drawbar and weighed between1400 and 2200 kg (3000 to 5000 lb). Adoption of the small gasoline tractor was fueled by its success in demonstrations and tests. In 1908, public demonstrations in Winnipeg showcased the powerful potential of the small tractor (Schueller 2000). Nebraska passed a tractor test law in 1919, requiring manufacture claims of tractor horsepower and weight to be verified. This mandatory testing provided credibility to manufacturer claims and validated the farm-worthiness of some models.

Around 1916, Henry Ford introduced the Fordson tractor (Schueller 2000). It was lightweight, mass produced at low cost, and was competitively priced. This small tractor eventually achieved three-quarters of the small tractor market share in the United States and around one-half of the market worldwide. In the mid-1920s, entrance of an even smaller general-purpose tractor, the International Harvester's Farmall model, facilitated tractor viability for more than simply plowing; tractors could now be the primary power source for secondary cultivation activities.

Starting around 1915, the number of tractors on U.S. farms increased dramatically. Farmers were encouraged to purchase tractors because labor

was scarce during wartime (Barker 1907). As World War I ended, the farm literature further suggested that a farm without a tractor was old-fashioned (Boss 1919). There were an estimated 20,000 tractors on U.S. farms in 1914. In 1915 alone, production of new tractors was greater than 20,000, with production volume lagging behind demand (Currie 1916). In 1917, over 62,000 tractors were produced and eighty-five new companies entered the field. The next year, 132,000 tractors were produced (Leichtle 1995). Peak production of approximately 800,000 tractors was reached in 1951. Today, United States agriculture is predominantly tractor-powered, with around 100,000 tractors sold yearly.

Several modifications to the gasoline tractor improved capabilities and facilitated an expanding array of cultivation options. Tractors must provide propulsion power across soft soils and traction can be a limiting factor. In the early 1930's, tractors still had steel wheels with jutting metal bars on the outside for traction (Ganzel 2003). By 1940, nearly all new tractors were equipped with rubber tires. These tires greatly improved traction and maneuverability of the tractors. The invention of rubber tires facilitated improved performance of cultivation implements by increasing tractor traction and providing more pulling force.   Rubber tires also improved maneuverability, which allowed for more precise cultivation.

One early method of attaching an implement to a tractor was with a drawbar, a steel bar to which the hitch of an implement was connected to the tractor with a clevis pin. The drawbar attachment went back to the earliest forms of agricultural mechanization. Horse-drawn implements usually had wheels and a connecting bar or loop to attach to the animal. Drawbar connections necessitated that each implement have its own running gear and

a separate way of being raised or lowered. Also, with many implements, a farmer had to stop at the end of each row, dismount, raise a cultivator or plow up, make a turn, dismount again, lower the implement, and then begin the next pass of the operation. Alternatively, separate individuals would have to ride on the implement behind the tractor and raise or lower it as needed.

The three-point hitch provided a means for raising and lowering an implement while the operator remained on the tractor, through a combination of linkage points (two on bottom, one on top) and hydraulics. Harry Ferguson invented this system in the late 1920's, and it came into production in the mid-1930's (Sanders and Feller 2007). The three-point hitch revolutionized cultivation equipment: tools could be lighter, more readily mounted to the tractor, safer, and no longer needed to have wheels. Almost every tractor today features a variant of the three-point hitch system.

In addition to a tractor supplying tractive power, the development of power take-off (PTO) and hydraulic systems on tractors provided alternate means of transferring power to connected implements. A PTO provides rotary power to implements. With invention of the PTO, tractor-propelled cultivation implements like the rototiller and the brush hoe could function.   The addition of hydraulics to tractors further facilitated development of implements that utilized hydraulic power to adjust tool depth or orientation. Hydraulic steering aided the guiding of a tractor within crop rows by improving steering precision and decreasing the force necessary to change tractor direction. With the addition of batteries and generators in tractors, the potential to integrate electrical power into implements became a further option.

Between 1900 and 1960, gasoline was the primary fuel source, with kerosene and ethanol also being burnable in the same engine. The use of

diesel engines became more prominent by the 1960's, and soon became the preferred power source for farm tractors (Saunders and Feller 2007). Diesel engines offered advantages to the farmer relative to gasoline engines: more fuel efficiency, longer lifespan, and less explosive tendencies. The higher torque output of diesel engines provided more pulling power for implements on a weight-to-weight basis. This in turn increased the feasibility of tools which were heavier and larger. In general, tool performance benefited from having more power available to move soil.

The tractor was continually refined during the remainder of the 20th century to be more efficient, productive, and user-friendly. Contemporary tractors perform four times the work per gallon of fuel compared to early 1900's tractors (Schueller 2000). Although there were 186 tractor manufacturers in 1921, by the turn of the century only two U.S. corporations, Deere and AGCO, were producing large numbers of tractors (Schueller 2000). In addition, Fiat-controlled CNH, which included the remnants of International Harvester and Ford, has maintained a substantial presence.

The Course of Innovation in Cultivation Equipment Evolution

Mechanized agriculture was rooted in Europe. While farmers in Europe began to benefit from some of the mechanization occurring during the Industrial Revolution, America was still in a fledgling state, and pioneer farms were using more basic implements (Blandford 1976). However, once farming became established in the United States, with local sources of equipment, and a rapidly expanding array of manufacturers, machinery development in the U.S. soon evolved to the forefront. America has large expanses of fertile farmland, compared with the relatively small fields of Europe. With the vast

acreage in the United States, particularly in the Midwest, there was a greater potential for advancements in large and complex equipment.

European inventors did much of the early work designing plows and harvesting equipment. By the late 1800's, however, American inventors including Cyrus McCormick and Jerome Case began bringing their machines to shows in England and France (Johnson 1976). Machinery shows in the middle of the 1800's were popular in Europe, and American inventors went to great lengths to bring their machines to compete. Machinery trials soon made their way to America, and to this day, these trials offer an important means of disseminating information about agricultural equipment. Farm magazines and papers of the late 1800's such as the *Prairie Farmer* and the *Wisconsin Agriculturalist* provided farmers with information about new inventions and gave equipment manufacturers a location to advertize their machines (Johnson 1976).

One example of the influence of exhibitions or trade shows on cultivation tool evolution is the integration of the Garret lever horse-hoe, an early design for a steerable horse-drawn cultivator. This design was shown in the agricultural machinery section of the Great Exhibition of 1851 in London (Blandford 1976). The Garret hoe had fourteen steerable hoes (two hoes per row), with levers to raise or lower the hoes, and adjustable wheel heights. After successful demonstration of this tool, its virtues were recorded in the 1902 Encyclopedia Britannica:

> Garrett's horse-hoe is admitted to be the best implement of its kind. It can be used for hoeing either beans, turnips, or corn, as the hoes can be adapted to suit any width betwixt rows, and the axle-tree being movable at both ends, the wheels, too, can be

shifted so as to be kept between the rows of plants. The shafts

can be attached to any part of the frame to avoid injury to the

crops by the treading of the horses. Each hoe works on a lever

independent of the others, and can be loaded with different

weights, on the same principle as the coulters of the corn-drill, to

accommodate it to uneven surfaces and varying degrees of

hardness in the soil. (Anon. 1902)

When tractors first began to be used, these steerable cultivators were modified

for use with a tractor. Early designs still required a man to follow behind the

cultivator to correct for deviations in tool movement, while later changes to the

tractor mountings allowed for cultivation to be done entirely by the tractor

operator.

Farm inventions were not limited to Europe and the United States. For

example, creation of the rotovator (rototiller) in 1912 is credited to an

Australian engineering apprentice, Arthur C. Howard (Blandford 1976). He

made notches in the blades of an ordinary disc harrow so that they formed the

still-used L-shape. This rototiller was powered by a range of gasoline engines,

and found early success in Australia. The rototiller design is still in wide use

today.

Farm invention in the United States started in the east. John Deere

from Vermont invented the steel self-polishing plow, which is largely credited

with opening up the west (Johnson 1976). Cyrus McCormick from Virginia

founded the large farm machinery company known as International Harvester.

Soon, however, with the bulk of farm acreage in the Midwest, manufacturing

transitioned to such areas – particularly industrial cities like Chicago, IL,

Racine WI, and South Bend, IN (Johnson 1976). People were migrating west;

immigrants were arriving; the Gold Rush of 1849 spurred people westward; and, the Civil War of the 1860's pushed people out of southern and eastern battlegrounds. Farming, and servicing the needs of farmers, were promising opportunities.

Johnson (1976) described American farmers as having a "love affair" with machinery and invention. Those who farmed were engaged in a physical effort which provided the impetus to develop efficiencies that might speed up processes (e.g. plowing, cultivation, harvesting) or increase the success of a given operation. Farmers needed to improvise, to come up with solutions, adaptations, or improvements to suit their needs. Self-reliance and renaissance abilities facilitated new inventions and modification of old inventions. Johnson (1976) stated that "virtually all the early inventors of farm machinery, later to become agribusiness industrialists, were blacksmiths or wheelwrights". Tools from different manufacturers were given names like Bellevue and Buckeye, Corn Dodger, New Captain Kidd, Yankee Doodle, and Old Reliable (Wendel 2004).

As an idea for a piece of cultivation equipment gained popularity, a local blacksmith could often copy the design, or fashion a competing design without issue (Johnson 1976). It was a matter of attrition between inventors and their companies; those without sufficient funds, production capabilities, or talent in distribution and marketing, were forced out of business. Small manufacturers were purchased by larger manufacturers, and the field narrowed as competing companies merged or bought each other out. For example, the Emerson Manufacturing Co. goes back to 1852. They produced a range of specialty cultivation equipment like the aptly named "No. 1 Beet Cultivator" (Wendel 2004). This company was bought out by J.I. Case Co. in 1928. Then,

Massey-Harris Co., Ltd., Toronto Ont. purchased the Case Co. in the same year, providing Massey-Harris with a base to operate from in the United States.

In 1880 there were at least 2000 manufacturers of farm implements operating on a combined capital of 60 million dollars (Currie 1916). By this time, early patents had run out, freeing individuals and small businesses to manufacture plows, cultivators, and other agricultural implements. However, raw material costs were increasing. The labor force was becoming organized, and with that came a demand for higher wages. By 1890, there were under 1000 farm implement manufacturers remaining. Within the next ten years, several hundred more manufacturers went bankrupt or left the business. By 1906, there were approximately 600 farm implement manufacturers remaining. Deere Co. was one manufacturing giant which came about through this era of absorption and expansion. By 1916, this one company alone was worth five million dollars more than the sum worth of all the manufacturers operating in 1880 (Currie 1916). Deere Co. maintained a market advantage by investing in agricultural equipment lines across the country: factories for plows, hay-making, wagons, and planters.

In the years preceding World War I, agricultural universities were beginning to invest in extension services and experiment stations (Johnson 1976). By 1910, eight state colleges were offering courses in agricultural engineering (Rumeley 1910). While research and education improved a number of aspects of farm management at this time, there were fewer contributions in the way of mechanical inventions.

The 1930's were a time when smaller, simpler farm machines were being transitioned into larger and more complex pieces of machinery (Johnson

1976). Row crop tractors began to make an appearance, facilitating development of tractor-driven cultivation equipment (Wendel 2004). Early in 1930, the Oliver Company refined the row crop tractor by placing two small drive wheels in the front close together. These closely spaced wheels made it easier to accurately drive the tractor through evenly spaced crop rows (Ganzel 2003).   Wendel (2004) notes that farmers were eager to purchase a combination row crop tractor and cultivator.

Although farm equipment mechanization increased in the 1930's, the onset of the Great Depression made it economically unfeasible for farmers to acquire new pieces of equipment (Wendel 2004). Between 1930 and 1932, tractor production dropped from around 200,000 tractors a year to only 19,000 (Ganzel 2003). The number of tractor companies declined as well, from around 90 companies in 1920 to only nine major manufacturers by 1933. During this time it was simply not possible for growers to purchase new cultivation equipment, or for manufacturers to invest time and money into new tools.

World War II was the separation period during which horse-drawn agriculture was largely phased out and farming became increasingly mechanized. When World War II began, the production of farm machinery came to a near-halt (Wendel 2004). Only after 1945, when the war had ended, did the production of machinery begin again in earnest. By this time, a number of smaller equipment manufacturers had disappeared.   After the war, small-scale production of horse-drawn cultivation equipment lingered on, up into the early 1950's.

Following World War II, urbanization and industrialization in the United States swelled. Capable farm workers became harder to find, and, in turn,

more expensive to employ. Work in city factories became available. The drudgery of hand weeding and farm tasks could not match the new-found luster of industrialized work (LeBaron et. al. 2008). Pressure was mounting for farms to become increasingly mechanized. Weed control by hand, hoe, and cultivator were labors of skill – a concentrated attentiveness was needed to remove weeds growing close to a crop. Carelessness in weeding, mediocre operators, or limitations in equipment capability would result in direct injury to the crop. Weeds that were left uncontrolled would further reduce yields.

Up until around the 1950's, cultivation was the primary weed management strategy in most vegetable crops. However, following the introduction of herbicides in the mid-1940's, mechanical weed control was rapidly replaced or supplemented with chemical weed control (Kouwenhoven 1994). The herbicide 2,4-D came into the marketplace in 1945 (Ganzel 2003). In 1946, manufacturers sold around 600,000 pounds of product. The next year, manufacturers sold over 5 million pounds, a nearly eight-fold increase in one year (Ganzel 2003). By 1962, companies were marketing around 100 herbicides in over 6,000 different formulations (Gianessi and Reigner 2007).

The birth of herbicides placed a new selective pressure on cultivation equipment. When weeds were controlled with herbicides, the crop was not subjected to root disturbance or injury from mechanical cultivation; weed control, particularly in-row weed control, was reliably improved; and, less manpower and tractor operations were needed (LeBaron et. al. 2008). In some ways, herbicides, and pesticides as a whole, represent the latest, predominating power source on the farm: they provide a means by which to produce much more than before, with greater levels of efficiency and with a

reduction in manpower beyond what was previously thought possible. A small fraction of the population could now provide food for an increasingly larger majority.

To date, chemical weed control has been employed successfully in nearly all crops, and across the globe (LeBaron et. al. 2008). However, with increasing market demand for organic produce, and public and farmer awareness of environmental damage caused by the use of some farm chemicals, there has been revived interest in mechanical tools.

At present, the majority of farm equipment is built and sold by large businesses. Product development costs, and the complexity of materials and of the product itself, restrict the small-scale inventor and manufacturer. Most cultivation implements we have today have not been greatly changed in over 100 years. However, small European companies now lead the way in new tool advancements with companies and equipment including Bärtschi-FOBRO's brush hoe (Switzerland), Kress and Companies' Finger Weeder (Germany), and the CMN Companies' Couch Grass Killer (Denmark).

Modeling the Rise and Fall of Power Sources and Cultivation Tool Diversity Over Time

The primary forms of agricultural power: human, horse, steam, internal combustion, and chemical have in large part dictated the level of agricultural production. The overarching chronological distribution of on-farm power sources is illustrated in Figure 1.4 and is based on data extracted from the literature (Currie 1916; Johnson 1976; Rumeley 1910; Timmons 1970). Direct interactions between different power sources occur within each major shift from one power source to the next. Increasing use of horses decreased the dominance of direct human labor. Likewise, the integration of the internal

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combustion engine signaled the rapid decline of animal-powered agriculture. Steam power, while relevant to agriculture, was not a direct power-shift from horsepower; rather, steam power provided the foundation for building the success of the internal combustion engine.

The integration of chemicals provided a direct alternative to handweeding. Gianessi and Reigner (2007) found that to remove herbicides from modern U.S. agriculture would require employing 70 million workers to control weeds via cultivation and handweeding. With a current U.S. population of around 300 million, more than a fifth of today's population would be engaged in weed management on the farm. With herbicides, handweeding and hoeing were no longer the end-all for managing weeds. Fewer individuals could now do much more.
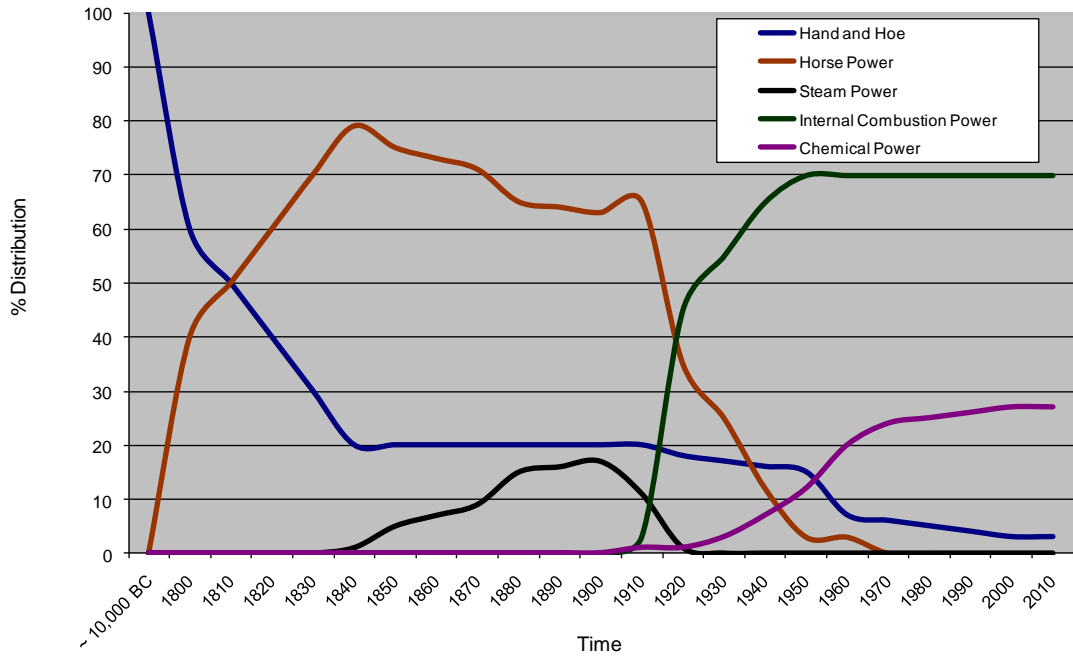
Figure 1.4. The relative dominance of unique forms of agricultural power over time.

The extent of cultivation tool diversity has been dependent on changes occurring in agricultural power sources. Figure 1.5 models the relative diversity of hand, horse, and tractor-powered tools over time (Blandford 1976; Currie 1916; Ganzel 2003; John 1973; Leichtle 1995; Rumeley 1910). Within the relevant timeframe of each cultivation-power source there is a point, near to when the power source is most dominant, where tool diversity peaks. This is where there are numerous manufacturers and designs being used by farmers, and where regional preferences and manufacturers are in varied abundance. Thereafter, the cultivation tool market narrows and there is survival of only those companies who have successfully blended inventiveness, quality of product, fortuity, organization, and business acumen.
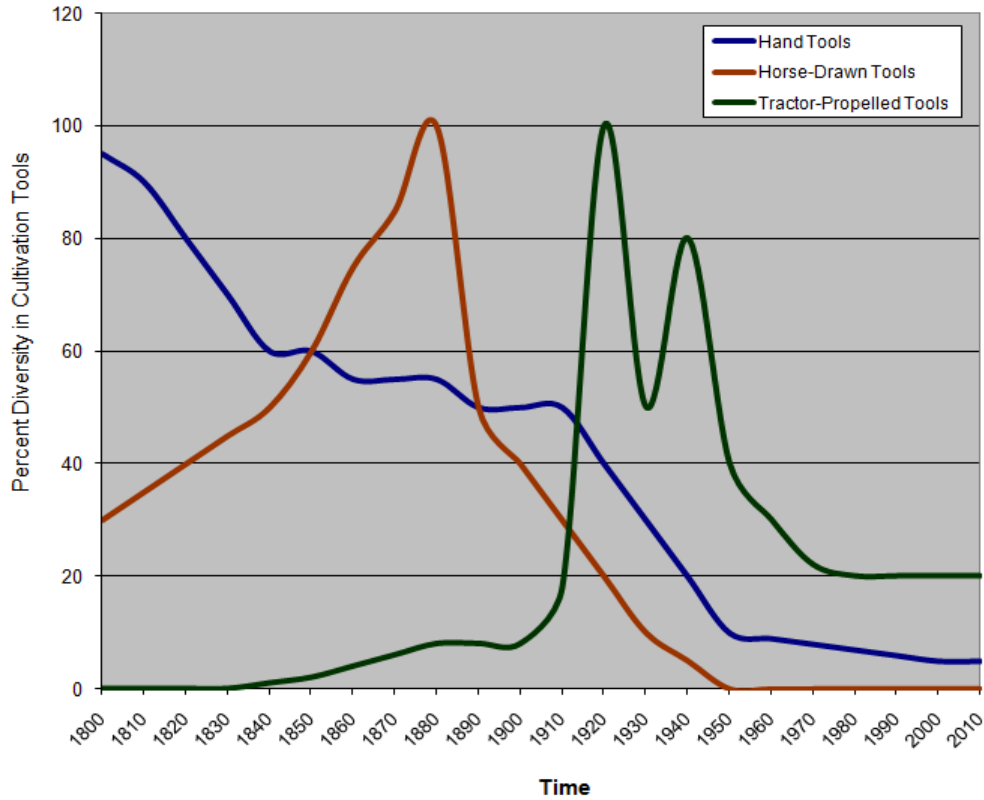
Figure 1.5. The relative diversity in hand, horse, and tractor (steam and internal combustion) powered tools over time.

Cultivation tool diversity can be correlated to the relative mobility of farmers and manufacturers. Early hand tools were often made on-farm, by local blacksmiths and by small regional manufacturers. With limited mobility in the 1800's, tool designs evolved to suit the needs of a small local farming base, somewhat independently of tool designs evolving elsewhere. Thus, the timeframe during which a diverse range of hand tools existed in the U.S. was relatively lengthy. By the time on-farm horse usage peaked, and likewise with tractor usage, countrywide interconnectedness and mobility had substantially increased. Farmers now had access to a wider regional pool of cultivation equipment; large manufacturers were shipping tools across the country; designs were being patented; and, farm equipment literature was being widely disseminated. The outcome of increasingly unified agriculture was a decrease in the duration in which a diversity of tools could exist in the market. Once dominant tool companies became established, tool variety narrowed to only these companies' offerings.

Cultivation tool diversity was also directly influenced by major developments in society at large. The Great Depression brought development of new farm equipment to a virtual halt. World War II signaled a shift from agricultural machinery production to wartime production efforts. Both of these events decreased the diversity in available farm equipment (Figure 1.5).

A facilitating factor in early cultivation tool diversity was the number of farmers. In the years preceding 1850, at least 65% of the population lived on farms, where seasonal removal of weeds was a primary duty (Gianessi and Reigner 2007). By 1910, there were over 6 million farmers in the United States and almost 40% of the population lived on farms (Currie 1916). Thus, during these years there were a large number of potential customers, each

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with different ideas on what types of cultivation tools would be the best investment.   Likewise, there were a large number of tool-producing companies trying to fill these on-farm needs.

Over time, the number of farmers and farms have decreased. By 2005, there were fewer than 2 million operating farms and less than two percent of the population lived or worked on-farm (Ritter 2005). The current reliance on chemical means of weed control further decreases farm demand for cultivation equipment. The specialization of farms, and the decline in the number of agricultural individuals, currently limits the market's ability to support production of a diverse array of cultivation tools.

The history of cultivation tools has been directly related to the evolution in power sources on the farm. New tool invention has consistently been spurred by a desire to harness the capability of new power sources. Despite thousands of variants in cultivator designs appearing over the last few centuries, only a limited number have made it to the present day. Revived interest in cultivation tools hinges on their potential resurgence in organic agriculture and in alternative systems which restrict the use of conventional herbicides or promote the integrated use of cultivation. Demonstrated viability of guided-cultivation systems, robotic cultivators, and novel tool designs may help spur a renaissance in cultivation on the farm.

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Chapter Two

Design, Construction and Evaluation of Two Novel Cultivation Tools

Abstract

Cultivation is a critical component of organic weed management and has relevance in conventional farming. Limitations with current cultivation tools include: high purchase and maintenance costs; limited efficacy; excessive soil disturbance; and, marginal applicability across a range of crops, soil types, soil moisture conditions, and weed growth stages. The objectives of this research were: to design and construct two cultivators that would be cost effective and simple to operate; to compare the weed control potential of both novel tools directly to that of a conventional S-tine cultivator; and, to evaluate crop response when these tools were used in transplanted pepper and broccoli. Two new tractor-mounted cultivators were designed and constructed as loose extractions of antique hand-held tools. The first tool, a block cultivator, has a flat surface in the front of the tool which rests against the soil and limits the entrance of a rear-mounted blade. The second tool resembles a stirrup hoe, where a horizontal steel blade with a beveled front edge slices through the upper layer of the soil. Block and stirrup cultivators were mounted on a toolbar with a traditional S-tine sweep, so that the novel cultivators could be compared directly with a common standard. In 2008, the tri-part cultivator was tested in 20 non-crop field events. In each event, four replicated cultivations were made at speeds of 2, 6, or 10 KPH. Weed survival and reemergence data were collected from the cultivated area of each of the three tools, at each cultivation speed. Environmental data were also collected at each event. A multivariable model was created to assess the importance of cultivator design, and environmental and operational variables, on post-cultivation weed survival. Additional trials in 2009 evaluated the yield response of bell pepper and broccoli to narrow and wide cultivations with each

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of the three tools. The influence of cultivator design on post-cultivation weed

survival was highly significant (P<0.0001). Averaged across the three tested

speeds, the block design provided significantly greater weed control than the

sweeps in 17 of the 20 cultivation events, and equivalent control in the other

three cultivation events (P≤0.10). The stirrup design significantly improved

weed control in 6 of the 20 cultivation events; provided control equivalent to

the sweeps in 13 events; and, lowered control in one event. Of the 11

individually assessed environmental and operational parameters, seven had

significant implications for weed control with the sweep; five impacted control

with the stirrup cultivator, and only one (surface weed cover at the time of

cultivation) influenced control with the block cultivator. When each cultivator

was used for inter-row weed control of bell pepper and broccoli, crop response

was identical. The block cultivator, because of its increased effectiveness and

operational flexibility, has the potential to improve inter-row mechanical weed

management.

Introduction

Cultivation can effectively manage weeds, and is a mainstay of many

organic weed management programs (Gianessi and Reigner 2007; Ryan et al.

2007). Cultivation has also been successfully integrated with the use of

herbicides on conventional farms. There are many different cultivation tools

on the market (Bowman 1997). Weeds are controlled by burial, uprooting, root

desiccation, and/or a physical separation or crushing of plant parts (Toukura et

al. 2006). A number of papers have been published regarding the use of

various cultivation implements within a wide range of cropping systems (Colquhoun et al. 1999; Mohler 2001; Pullen and Cowell 1997; Rasmussen 1992).

Limitations with current cultivation tools include: high purchase and maintenance costs; marginal efficacy; excessive soil disturbance; stimulation of latent weed seed germination; and, narrow applicability across a range of soil types, soil moisture conditions, and weed growth stages. There is a need for a cultivation implement that can address some of the limitations of current tools. Serviceable improvement in weed control is the impetus behind creation of new designs. The objective of this research was to design and construct two novel tractor-propelled cultivation implements, and then, to evaluate whether these new tools could address some of the aforementioned limitations and have adequate crop safety.

Validating a new cultivator design requires assessment of a range of operational, environmental, and efficacy criteria. A new cultivator should require a minimum of force (energy) to be moved through the soil. Draft, or drawbar pull, is the force required to drive an implement in the direction of travel (ASABE 2006). The type and size of an implement can dictate operational speed, power, and fuel requirements (Michel et al. 1985).   Draft is directly proportional to the width of an implement and the speed at which it is pulled (Grisso et. al 1994). Draft is also dependent upon operating depth and the specific arrangement of the tool (Upadhyaya et al. 1984). A cultivator which operates at a reduced depth and which allows soil to pass through (i.e. free-flow through the implement), rather than one that attempts to push or pulverize the soil, should decrease draft. If a novel cultivation tool lowered operational draft power requirements, relative to a conventional cultivation

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tool, it would decrease the tractor horsepower requirement and permit increased fuel economy during cultivation.

A mechanical weed control implement needs to be economically viable. A cultivator should not be cost-prohibitive for small-to-medium sized growers. Replaceable parts should be relatively inexpensive and easy to change. For instance, the Baertschi brush hoe, despite its weed control effectiveness, is expensive to purchase, time consuming to modify to different row spacings, and requires a second operator behind the tractor to steer the tool (Colquhoun and Bellinder 1997). A structurally simple cultivator would limit undue expense during manufacture and would minimize the potential for complicated components to break or function poorly.

Cultivation tools for small and medium-sized vegetable growers are often used in multiple crops grown with a wide range of between-row spacings. A flexible implement that could be readily adjusted to different row widths would be useable in multiple cropping systems. A classic example of an adaptable design is a sweep mounted on an S-tine or fixed shank. This design has existed for centuries, yet remains a farm favorite even today due to its ease of use, adjustability, low purchase cost, and low maintenance costs (Currie 1916; Parker 2008).

Soil conditions impact cultivator performance. Kurstjens and Perdok (2000) noted that to facilitate a broader acceptance of mechanical weed control in agriculture we must expand the range of weather conditions under which soils remain workable by cultivation. High soil moisture during and after a cultivation can reduce efficacy (Bond et al. 2007). Terpstra and Kouwenhoven (1981) found that weed kill with a duckfoot sweep declined from 90% when the soil remained dry post-cultivation, to 78% when the soil was

wet post-cultivation. Some implements perform poorly in certain soil types and/or conditions. For example, basket weeders are generally ineffective in stony or compacted soil because the stones clog the baskets or the baskets fail to cut through a crusted soil surface (Bowman 1997). Weed control with a harrow is more effective in sandy soils than in clay soils (Van der Weide and Kurstjens 1996). Ideally, a new cultivation tool would perform satisfactorily across a range of soil moistures, as well as, variations in soil texture, structure, and health (e.g. organic matter content, clay content, size and degree of stoniness).

Weed species, size, and density influence cultivation efficacy. Some cultivators will control weeds within only a narrow size range. Flex-tine weeders are best suited for control of weeds in the white-thread to cotyledon stage (Bond et al. 2007). High weed densities clog rotary hoes and spider wheels. Weeds with tenacious or deep root systems escape cultivation implements that operate primarily by uprooting. The performance of cultivation tools that bury weeds will generally decline as weed size increases. As weeds grow older, they are less likely to be fully covered by soil, and are more prone to break through a covering of soil (Kurstjens and Perdok 2000). An ideal cultivator would provide high levels of weed control across a broad range of weed species, sizes, and densities.

Speed of cultivation not only influences the time it takes to cultivate a field, but efficacy as well. Pullen and Cowell (1997) evaluated a harrow, sweep, brush hoe, and rototiller, and found that increased travel speed did not equally improve the performance of each implement. Increasing travel speed with a sweep cultivator has been shown to increase soil covering of weeds and thereby reduce weed survival (Kouwenhoven and Terpstra 1979). Pullen

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and Cowell (1997) suggested that a 5 km/hr travel speed is common with existing inter-row cultivators. One effective cultivation tool, a combination of intra-row rotating horizontal disks and inter-row sweeps, operates at a 1.8 km/hr travel speed (Tillet et al. 2007). Such a slow speed severely limits the amount of field area that can be cultivated in a given timeframe.

In cultivation of some row crops, speed is dictated by the sensitivity of the crop, size of the crop and weeds, and operator skill. Cultivation can be carried out at relatively high speeds when the crop is of an optimal size, resilient in nature, and/or the soil conditions are ideal. Narrow row spacing, the presence of large stones or soil clods, and/or high crop sensitivity necessitates precise cultivation, and thus a slower cultivation speed. An ideal implement would provide consistently high levels of weed control across a wide range of speeds.

The usefulness of a cultivation implement is ultimately determined by its ability to control weeds. Cultivation efficacy is strongly dependent on many of the aforementioned factors: soil conditions, weed variability, and travel speed. The inherent weed control potential of different tool designs is directly proportional to their flexibility to perform across a wide range of environmental and operational variables. Increased weed control with a single cultivation pass could reduce the need to make multiple passes. Minimizing repeated tractor field operations could result in time and energy savings, as well as reduce the potential for soil compaction (Ball 2006). All cultivation events have the potential to stimulate latent weed seed germination. Seeds of many weed species need light exposure to germinate (Milberg et al. 1996; Pons 1992). Cultivation events that minimize post-cultivation weed seed germination could decrease the frequency of later cultivations.

The objective of this research was to design, construct, and evaluate two unique inter-row cultivation tools that might address some of the shortcomings of current cultivators. Specifically, the goals were to design and construct two cultivators that would be cost effective and simple to operate and maintain; to compare the weed control potential of both novel tools directly to that of a conventional S-tine cultivator; and, to evaluate the potential for crop injury in transplanted bell pepper (*Capsicum annuum*) and broccoli (*Brassica oleracea*).

Material and Methods

Design and Construction of Novel Cultivation Tools

Designs for two new tractor-mounted cultivators were loosely extracted from patents of antique hand-held tools (Morgan 1903; Oakland 1928). These new cultivators were drafted with the aid of engineering software[1] and constructed in the Metal Technologies Working Lab at Cornell University. Costs of materials and time of construction were documented. The tools were designed specifically for mounting on a standard toolbar; this toolbar could then be attached to any tractor equipped with a three-point hitch.

One impetus behind design of the first tool, called a block cultivator, was a design for a hand-held tool patented in 1928 by M. Oakland (Figure 2.1). There are no current cultivation tools which resemble or function identically to the block cultivator. Views of the implement are shown in Figure 2.1. As the tool is pulled across the soil, a blade cuts in and lifts soil onto and over its wide, inclined surface. A flat block in the front of the tool rests against

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[1]AutoCAD 2008. Autodesk Inc., 111 McInnis Parkway, San Rafael CA 94903

Figure 2.1. The block cultivator. Clockwise from top: original illustration of a hand tool designed in 1928 by M. Oakland; top-down view, with the front of the cultivator to the right; rear view, soil disturbance after cultivation; side view, showing the tool shank extending upward into a toolbar clamp and the toolbar attached to a tractor via a three-point hitch; side view of block cultivator, with the front of tool to the left.

the soil surface. A rear surface behind the blade also rests against the soil. These two surfaces apply critical pressure on the soil while limiting penetration depth of the cutting blade.

A contributing model in the design of the block cultivator was a woodworker's block plane. With a block plane, a flat sole (base) regulates the depth of a mid-mounted cutting blade, facilitates evening out of uneven surfaces, and provides down pressure against the wood (Noyes 1910). Likewise, with the block cultivator, the flat blocking to the front and rear of the blade smoothes the soil surface and allows the tool and toolbar weight to rest heavily against the soil without excessive blade penetration.

Mechanisms for tool adjustment were built into the prototype to allow for configuration flexibility. The blade depth can be adjusted from 1.3 to 5.1 cm. The forward block can be adjusted from a horizontal position to an upward angle, to minimize soil buildup at the front of the tool. To each side of the front surface are 1.3 cm-thick extensions which project 1.3 cm below the cultivator frame. These extensions aid in cutting the soil surface on each side of the cultivator, prior to the blade entering the soil area between each protrusion. All testing was conducted with the blade at the shallowest setting (1.3 cm-depth, 20° blade angle) and the forward block angled upward in the front.

The tool has been designed for durability and use in potentially stony soils. The frame of the tool was constructed of 1.3 cm mild flat steel. The 1.3 cm-thick blade was beveled to 45 degrees on the upper edge. Hard surfacing was added to the lower side of the leading edge to reduce blade wear. Twenty centimeters were left open between the rear edge of the front surface and the leading edge of the blade to allow soil-surface rocks of less than a 20 cm diameter to pass through. Angled arms on each side of the cultivator

frame extend upward to a central plate, from which a 1.9 by 5.1 cm hardened steel shank extends upward into a standard, pre-manufactured toolbar clamp[2].

This cultivator could be dimensionally altered to work within different row crop spacings. In its current form, two block cultivators are used in tandem for cultivation of a single inter-row space. Adjustment of tool position on the toolbar of one or both cultivator units allows for cultivation of a wide range of inter-row widths. The current design utilizes a single-pivot point for adjustment of the rear-mounted blade. This means that as the depth of the blade increases, so does the blade angle. An alternate version should incorporate a means of depth adjustment that would not also change the blade angle.

The second tool, called a stirrup cultivator, is similar in appearance to a stirrup hoe, where a horizontal steel blade slices through the upper crust of the soil (Figure 2.2). The impetus for creation of this design came from an illustration of a hand-held tool patented in 1903 by E. B. Morgan (Figure 2.2). Structurally, the stirrup cultivator is distinct from current cultivation devices. This tool, like the block cultivator, was designed specifically for mounting on a standard toolbar. The tool incorporates a horizontal steel blade, with an angled front and rear edge, to slice through the upper crust of the soil. The blade is approximately 33 cm-long on the horizontal portion, 7.6 cm-wide and 1.3 cm-thick. The wide span of the tool permits large rocks to pass through. The thickness of the blade forces soil to move up, over, and down the course of the blade. This movement contributes to increased soil aggregate

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[2]Bigham Brothers Tool Bar Shank Clamp (806-402). Bigham Brothers, Inc. 705 E. Slaton Rd., Lubbock TX 79452

Figure 2.2. The stirrup cultivator. Clockwise from top: original illustration of a hand tool designed in 1903 by E. B. Morgan; front and side view; soil disturbance after cultivation; rear view of the cultivator, where the tool shank extends upward into a toolbar clamp; top-down view.

separation relative to a thinner, flatter blade. The front and rear of the blade's upper surface were beveled to 45 degrees. This bevel extends upward on each side of the blade as it curves to meet the angled arms to which it is attached. This bevel facilitates cutting into the soil.

The tool was constructed to be strong and flexible. A layer of hard surfacing was added to the bottom of the leading blade edge to slow wear. The blade was also designed to be reversible, to increase service life. Two 1.3 cm-thick arms bolt to the blade, one on each side, and these arms angle upward into a 1.9 cm-thick central plate. From this plate, a hardened steel shank extends upward, and into, a standard toolbar mounting clamp[2]. Holes in the central plate allow for the tool to be held in a horizontal position or angled to the front or rear. Tool depth is regulated by the tractor operator through raising or lowering the 3-point hitch, or by raising or lowering the shank height within the toolbar mounted clamp. In these trials, the tool was held in a fixed horizontal position and depth was restricted to between 2 and 8 cm.

Determining the Weed Control Potential of New Cultivation Tools

Both the block and sweep cultivator were mounted onto a single toolbar alongside a traditional S-tine sweep, so that the novel tools could be compared directly with this common grower standard (Figure 2.3). The S-tine sweep setup was removed from a currently manufactured inter-row cultivator[3]. Placing all three tools on the same toolbar minimized the potential for

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[3] I and J 2-row cultivator. I & J Manufacturing, 5302 Amish Road, Gap PA 17527

Figure 2.3. Rear view of the toolbar and the three different cultivator designs; from left to right: stirrup, sweep, and block cultivators.

variances incurred by using each tool as a separate entity, where different toolbars, separate timeframes of cultivation, and/or the necessity for larger field distances between cultivated areas, would complicate findings.

Field trials to assess the weed control potential of each cultivator were conducted in 2008 at the H. C. Thompson Vegetable Research Farm in Freeville, NY. The tri-part cultivator was evaluated in 20 independently replicated non-crop field events. Trials were block designs with four replicated cultivations at 2, 6, and 10 km/hr. Cultivation speed was the whole plot factor (randomized) and cultivator type was the split-plot factor. Plots measured 3 m-wide by 7.6 m-long. Each plot accommodated a 0.6 m-wide swath of each of the three cultivator types and a similarly sized swath of uncultivated soil, the weedy check.

Cultivators were held in fixed positions on the toolbar for the duration of the trial. The potential for tractor tire effects on cultivation efficacy was considered. Post-cultivation, but prior to collection of weed control data, weed counts in the two novel cultivator areas situated directly behind the tire tracks were compared directly to portions outside these tire tracks. With the block cultivator, there was never a measurable difference in weed number between tire track and non-tire track areas. With the stirrup cultivator, weed control in moist silt loam fields was generally higher in the cultivated area within the tire track as opposed to outside the tire track. In these instances, weed control data was collected solely from the cultivated area outside the tire track.

Half of the trials were conducted on field sites with an Eel silt loam soil (ESL[3]; fine-loamy aquatic mixed mesic Udifleuvant), the other half on sites with a Howard gravel loam soil (HGL[3]; loamy-skeletal mixed mesic Glossoboric Hapludalf). All field sites were moldboard plowed, disked and field cultivated, and then, natural weed populations were allowed to emerge. Trials were established in field areas where weed populations were relatively uniform. There were over 10 weed species present across all trials, with the most prevalent being: hairy galinsoga (*Galinsoga quadriradiata Cav.*), shepherd's purse (*Capsella bursa-pastoris* L. Medic.), purslane (*Portulaca oleracea* L.), common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), and large crabgrass (*Digitaria sanguinalis* L. Scop.)

Table 2.1 outlines the environmental variables collected from each cultivation event. Table 2.1 also includes, where applicable, the range of data collected for each parameter, across all cultivations. One day post-cultivation, a single permanent 0.25 m^2 quadrat was established in the center

Table 2.1. A description of the assessed environmental and operation parameters, and the range of variability present within the collected data.

Operation Parameters	Description	Range
Cultivator Design	Block, stirrup, or sweep cultivator	-
Cultivation Event	20 independently replicated cultivation trials	-
Cultivation Speed	2, 6 or 10 km/hr	-
Soil-Specific Parameters		
Soil Type	Silt or gravel loam	-
Soil Moisture Content	Gravimetric analysis was used to obtain a percent moisture at the time of each cultivation (7 cm-deep by 7 cm-wide cored samples, 4 per cultivation event)	7 to 22%
Surface Stoniness	Visual assessment of the percent of the soil surface covered by stone	0 to 70%
Surface Clod Size	Average clod size, categorized as small (less than 2 cm diameter), medium (between 2 and 6 cm) or large (> 6 cm diameter)	Small Medium Large
Surface Levelness	A measurement of undulations, or unevenness, in the field surface prior to cultivation. Assessed as the vertical distance between the highest and lowest points of the soil surface (cm), within a square meter.	3 to 10 cm
Weed-Specific Parameters		
Base Weed Population	Mean number of weeds present in a 0.25 m^2 area	20 to 342 weeds/ 0.25m^2
Mean Weed Size	Average weed size across the dominate weed species present (height in cm)	0.5 to 20 cm
Percent Surface Weed Cover	Digital photo analysis of weedy areas; provided a quantitative percentage of ground cover at the time of cultivation	0.1 to 83%
Precipitation Parameters		
Rainfall amount, on the day of cultivation	Rainfall volume on the day of cultivation (cm)	0 to 0.76 cm
Rainfall amount, in the five days prior to cultivation	Rainfall sum for the five days pre-cultivation (cm)	0 to 5.3 cm

of each of the three cultivated swaths in each plot. Thus, in each cultivation event there were 12 quadrats total for each cultivator: four at each of the three tested speeds. Four additional 0.25 m^2 quadrats were randomly established in the weedy check areas of each trial. The number of surviving weeds were individually tallied for each quadrat. Then, all surviving weeds in each quadrat were cut at their base (to minimize soil disturbance) and discarded. All quadrats were revisited fourteen days after cultivation. At this time, newly emerged weeds were counted, as well as weed escapes; i.e. those weeds that had appeared controlled at one day post-cultivation but had managed to regrow.

An assessment of the mechanisms of weed mortality was made one day after cultivation, in 0.25 m^2 quadrats (four per cultivator type, from plots cultivated at 6 km/hr). These areas were separate from those that had been monitored for post-cultivation weed survival. The soil in each cultivated area was carefully examined and sifted to identify the mechanism of weed death for each weed. Weed mortality was classified as due to desiccation, cutting/slicing, or burial. Recovery of all weeds controlled via burial was difficult. Therefore, the number of weeds killed by burial was determined by the number of unclassified weeds, relative to the base weed population per 0.25 m^2, after subtracting for weed survivors and weeds that had been killed via desiccation or cutting/slicing.

One day after cultivation, digital photographs were taken in each 6 km/hr cultivation tool swath, and in four random weedy areas. The camera was held approximately 1 m from the soil surface with a zero degree camera angle relative to the ground. Photos were uploaded into image analysis

software[4] that took the multi-colored images and converted them into binary images where green plant leaves were distinguished from the soil surface, dead plant residues, shadows and stones (per work done by Rasmussen et al. 2007). Software output provided a percentage of weed ground cover remaining one day post-cultivation with each cultivation tool, and the relative weed cover of uncultivated ground.

Data Analysis

Data were subjected to ANOVA. Fisher's protected LSD tests were utilized to compare cultivator performance in each independent cultivation event, with significance values set at $P \leq 0.10$. Then, a SAS statistical package[5] was used to model how operational and environmental variability impacted post-cultivation weed survival across all 20 cultivation events. The number of surviving weeds per 0.25 m^2, one day after cultivation, was set as the response variable w. The relationship between w and selected environmental and operational variables was modeled as: $g(E[w_i]) = \beta_0 + \beta_1 X_1 + \beta_2 X_2 \dots + \beta_{12} X_{12}$, with $X_1, X_2 \dots X_{12}$ representing each variable listed in Table 2.1 (except cultivation event); g was the log link function; and, $E(w_i)$ was the expected value of w. It was hypothesized that the two novel cultivators, relative to the S-tine sweep, would have greater flexibility to perform across a range of travel speeds and under diverse environmental conditions; that is, there would be a less significant relationship between these variables and weed survival.

A generalized linear mixed model was created using the PROC GLIMMIX function in SAS with a Poisson link function. The GLIMMIX

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[4] Imaging Crop Response Analyser. http://www.imaging-crops.dk. Rasmussen et al. 2007

[5] SAS 9.2. SAS Institute Inc, 100 SAS Campus Drive, Cary NC 27513

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procedure fits statistical models to data with correlations, where the response is not necessarily normally distributed. The generalized linear mixed model assumes normal (Gaussian) random effects but allows for data to be distributed within any exponential family. A Poisson distribution is a discrete member of the exponential family that adequately reflected the distribution present in the post-cultivation weed survival counts.

The generalized linear mixed model with the Poisson distribution was modeled using a log-link function, with the model fit on the log-lambda scale. Data was retained in its original form for presentation in figures. Weed density data from the weedy control areas were integrated into the statistical model as the variable base weed population (Table 2.1). Two-way interactions between cultivator design and selected environmental and operational variables were included in the model if they provided significant explanatory power. Step-by-step backwards selection, based on the Type III test for fixed effects in the PROC GLIMMIX procedure, was used to eliminate non-significant parameters ($P \geq 0.10$) and to create a final, reduced model. To determine how each tool's performance was uniquely predicated on operational and environmental conditions, a separate multivariable model was produced for each cultivator.

Determining Crop Injury Potential

Field trials using the block, stirrup and sweep cultivators were carried out in the summer of 2009 at the H. C. Thompson Vegetable Research Farm in Freeville, NY. Trials in transplanted bell pepper 'Lady Bell' and broccoli 'Premium Crop' were each conducted twice, at two different field sites. Soil at

both sites was a Howard gravel loam (HGL[3]; loamy-skeletal mixed mesic Glossoboric Hapludalf). Trials were randomized block designs with four replications.

The sweep cultivator was utilized in its original two-row configuration. The novel cultivators were mounted on the same toolbar, with the stirrup cultivator on each side of one row, and the block cultivator on each side of the other row. Cultivations were carried out with all tools adjusted to leave either a 15 or 24 cm-wide uncultivated in-row band. In-row areas of all treatments were handweeded as necessary. An uncultivated weedy check was included for comparison.

All field sites were moldboard plowed, disked, fertilized, and field cultivated prior to transplanting. Each plot was 1.5 m-wide and contained two 7.6 m-long crop rows. Transplants were mechanically transplanted 60 cm-apart, in rows spaced 76 cm-apart. Both broccoli trials were planted on April 20th and cultivations were made at 16 and 26 days after planting (DAP). Broccoli was harvested 51 DAP. Pepper trials were planted on June 1st and cultivations were made at 14, 38, and 46 DAP. All cultivations at 46 DAP occurred with the larger 24 cm-wide uncultivated area, necessitated by the increased plant size. Peppers were harvested at 65, 72, and 82 DAP.   In all trials, weed control and crop yield data were collected.   Data were subjected to ANOVA. Fisher's protected LSD tests were conducted to compare crop response to each cultivator, with significance values set at $P \leq 0.10$.

Results and Discussion

Cultivator Performance

Weed control varied by cultivator design. Full and reduced models of weed survival, as a function of operational and environmental parameters, are shown in Table 2.2. Notably, cultivator design was highly significant (p<0.0001). Averaging across the three tested speeds, the block cultivator provided significantly greater weed control than the S-tine sweep in 17 of the 20 cultivation events (P≤0.10) and equivalent control in the other three cultivation events. The stirrup design significantly improved weed control in 6 of 20 cultivation events; provided control equivalent to the S-tine sweep in 13 events; and lowered control in one event (data not shown). When weed survival was viewed collectively across all 20 cultivations, both novel cultivators significantly increased control. Relative to the S-tine sweep, the stirrup cultivator reduced weed survival by about one-third and the block cultivator reduced weed survival by greater than two-thirds (Figure 2.4). Similarly, when cultivator efficacy was measured by the percent surface area in weed cover one day post-cultivation, the block and stirrup tools outperformed the sweep (Figure 2.5). There is 95% confidence that the average number of surviving weeds in a 0.25 m^2 quadrat, at one-day post-cultivation with the block cultivator, will be between 3 and 5. In that same area, there would be between 8 and 13 weeds remaining after stirrup cultivation and between 11 and 19 weeds remaining after sweep cultivation. Thus, cultivation design was highly significant.

Table 2.2. The significance of environmental and operational parameters on weed survival one day post-cultivation. Insignificant parameters were eliminated from the reduced model.

Operational Parameters	Full Model Significance value (p)	Reduced Model Significance value (p)
Cultivator Design	<.0001	<.0001
Cultivation Speed	0.0778	0.0779
Soil-Specific Parameters		
Soil Type	0.2008	0.1555
Soil Moisture Content	0.0481	0.0361
Surface Gravel Cover	0.7208	-
Surface Clod Size	0.2228	-
Surface Levelness	0.0507	0.0819
Weed-Specific Parameters		
Base Weed Population	0.0367	0.0102
Mean Weed Height	0.9358	-
Percent Weed Cover, Untreated	0.0158	0.0033
Precipitation Parameters		
Rainfall Amount, on the day of cultivation	0.0727	0.0411
Rainfall Amount, in the five days prior to cultivation	0.0419	0.0312
Selected Interactions		
Design *x* Cultivation Speed	<.0001	<.0001
Design *x* Percent Weed Cover	<.0001	<.0001
Design *x* Soil Moisture Content	0.0071	0.0219
Design *x* Soil Type	<.0001	<.0001
Design *x* Surface Levelness	<.0001	<.0001
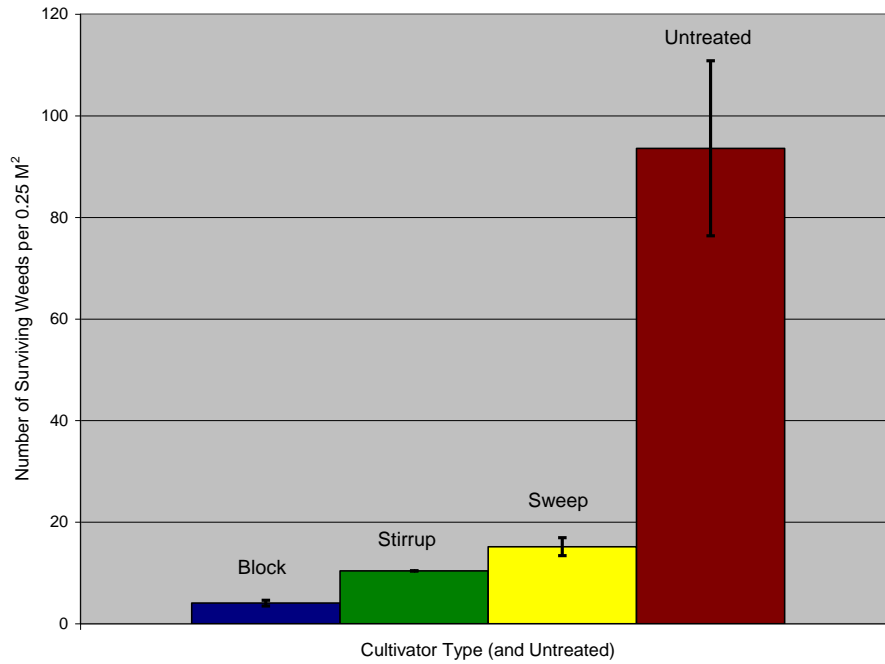
Figure 2.4. Weed survival, one day after cultivation with each tool and in the untreated area. Survival numbers were averaged across the twenty cultivation events and the three tested cultivation speeds. Standard error bars shown.

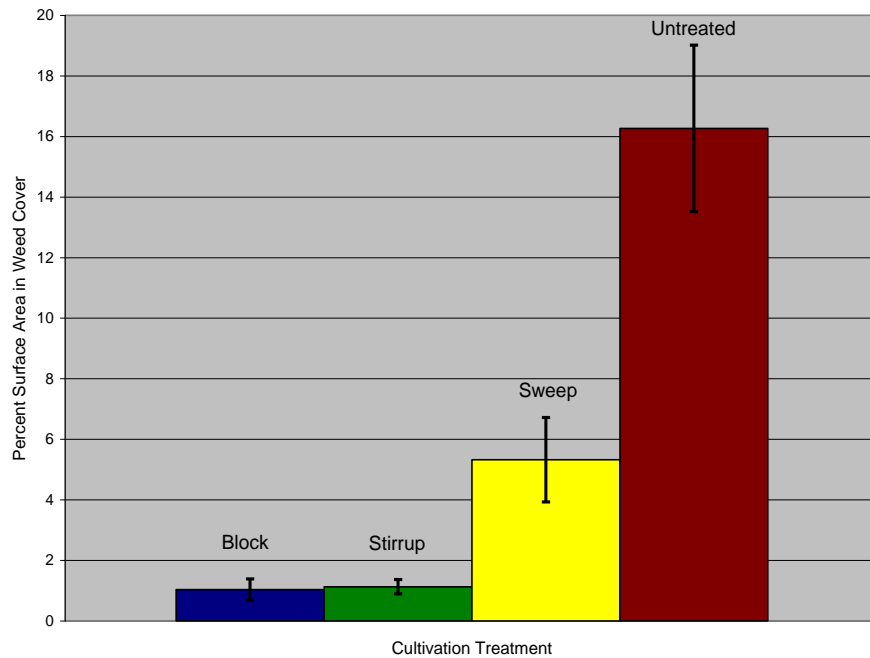**Figure 2.5.** The percent weed cover, one day after cultivation with each tool and in the untreated area. Weed cover data was averaged across the twenty cultivation events and the three tested cultivation speeds. Standard error bars shown.

Performance increased with the sweep cultivator as speed increased from 2 to 10 km/hr (Figure 2.6). With harrowing, increased speed is associated with improved weed control (Kurstjens and Perdok 2000; Pullen and Cowell 1997). Sweeps function most effectively by throwing soil, contacting it at speeds where aggregate separation is maximized. Decreased soil particle size enhances separation of weed roots from soil and provides more complete burial of small weeds.

In contrast, weed control with the stirrup and block cultivators remained relatively constant across the range of tested speeds (Figure 2.6). Both tools caused minimal soil throw; they were primarily slicing into and through the soil, and in the case of the block cultivator, compacting the soil to force apart aggregates. Increased travel speed increased the rate of the slicing and compacting, but did not increase the degree of aggregate separation. Farmers will often cultivate at a range of travel speeds, depending on crop sensitivity and operator skill. The new cultivators provide a more consistent level of weed control across varying cultivation speeds.

While some soil characteristics influenced cultivation, others were insignificant. Surface gravel cover and surface clod size did not measurably affect cultivation (Table 2.2). However, soil moisture at the time of cultivation remained an important variable (Table 2.2). Increased soil moisture led to increased weed survival with both the stirrup and sweep cultivators (Figure 2.7). In contrast, weed survival with the block cultivator remained constant throughout the observed moisture levels (Table 2.3). Data collected on rainfall levels; on the day of cultivation, and in the five days prior to cultivation, corroborates with the soil moisture data (Table 2.2).

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Table 2.3. The significance of environmental and operational variables on weed survival one day post-cultivation, for each cultivator design. Variables which significantly impacted weed survival (P≤0.10) are shown in bold.

	Sweep	Stirrup	Block
Operational Parameters	*Significance value (p)*	*Significance value (p)*	*Significance value (p)*
Cultivation Speed	**0.0027**	*0.1469*	*0.9080*
Soil-Specific Parameters			
Soil Type	*0.1587*	*0.6782*	*0.3813*
Soil Moisture Content	**0.0436**	**0.1073**	*0.1537*
Surface Stoniness	*0.5450*	*0.9814*	*0.8982*
Surface Clod Size	*0.1153*	*0.3321*	*0.4680*
Surface Levelness	**0.0172**	*0.4375*	*0.1358*
Weed-Specific Parameters			
Base Weed Population	**0.0135**	**0.0875**	*0.7594*
Mean Weed Size	*0.5219*	*0.3778*	*0.8810*
Percent Weed Cover, Untreated	**0.0184**	**0.0415**	**0.0583**
Precipitation Parameters			
Rainfall Amount, on the day of cultivation	**0.0624**	**0.0122**	*0.9588*
Rainfall Amount, in the five days prior to cultivation	**0.0247**	**0.0812**	*0.3701*
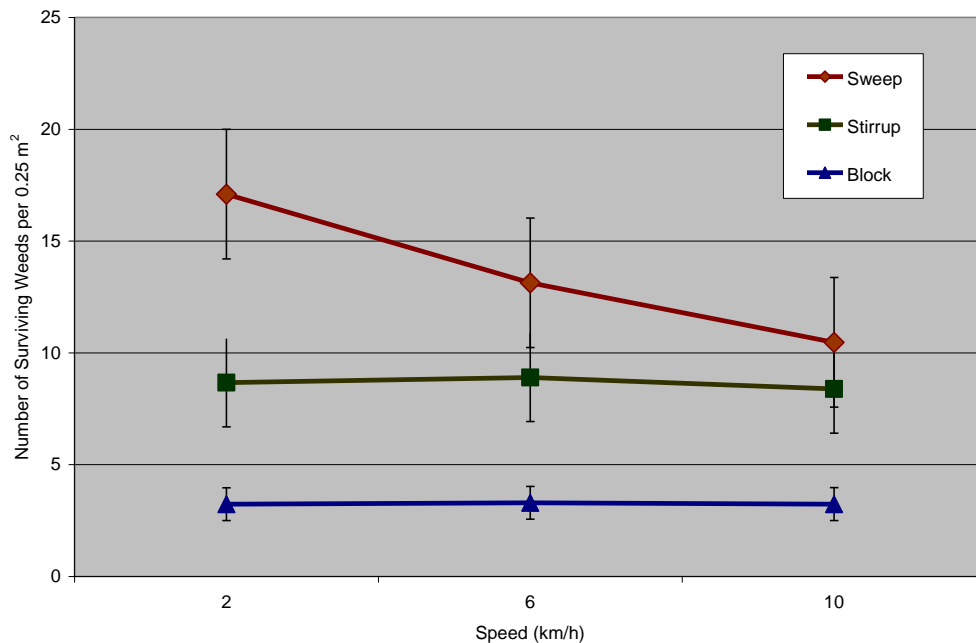
Figure 2.6. The impact of cultivation speed on weed survival, one day post-cultivation. Standard error bars shown.

However, base weed populations were generally higher in cultivations where the soil moisture was higher. Thus, it is possible that the differences in cultivator efficacy attributed to soil moisture are a result of differences in the ability of each cultivator to control varying weed densities. The observed trends in Figure 2.7 could simply reflect that the block cultivator was able to control higher weed densities than ether the sweep or stirrup designs. Base weed population did have a significant impact on post cultivation weed survival with the sweep or stirrup, but was non-influential with the block design (Table 2.3). Nevertheless, if we assume that weed numbers will generally be higher in moist soil conditions, then the block cultivator appears more capable in such a situation.

25

20

Number of Surviving Weeds per 0.25 M^2

15

Sweep
y = 0.6599x + 5.4725

10

Stirrup
y = 1.0464x - 4.8343

5

Block
y = -0.1152x + 5.5973

0

6   8   10   12   14   16   18   20   22

Percent Soil Moisture (from 0 to 7 cm depth)
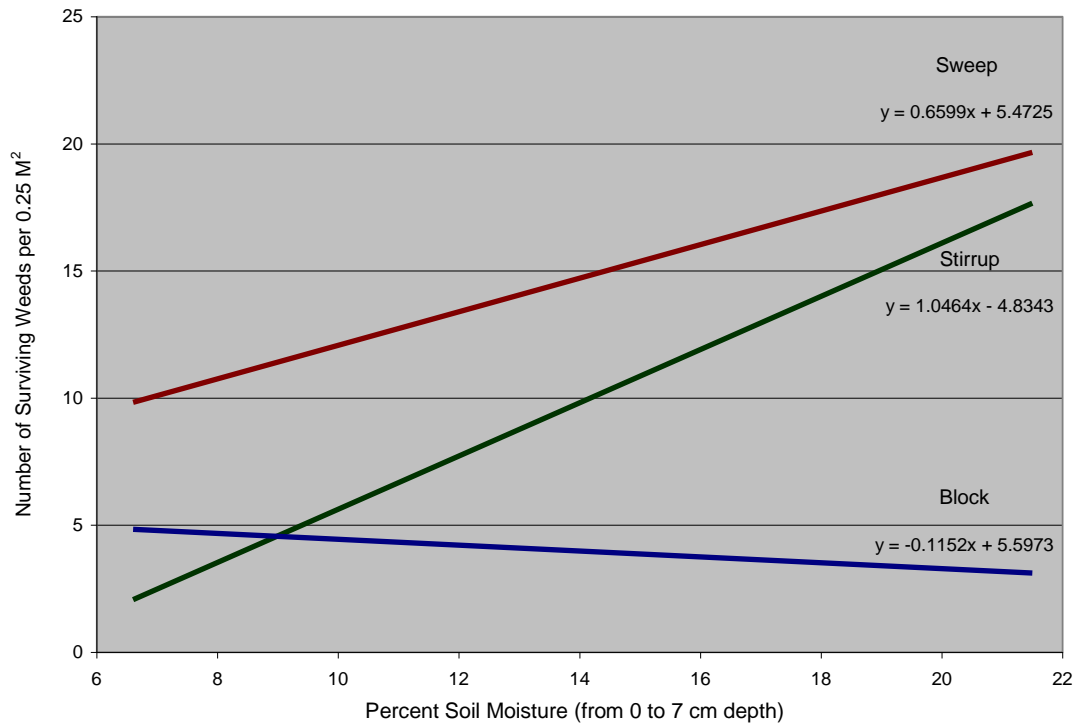
Figure 2.7. The impact of soil moisture on weed survival with each of the three cultivators, one day post-cultivation.

Higher moisture levels reduced the capability of the sweep and the stirrup to separate soil aggregates. Mohler et al. (2000) noted that when soil clings to seedling roots there is a lower chance for weeds to be buried or weed roots to desiccate. In contrast, the block cultivator compacted aggregates prior to entering the soil, breaking apart more of these aggregates and separating more weeds from soil – despite the tendency of moist soil particles to cohere. In soils that tend to become cloddy with increasing wetness, the downward pressure of the block cultivator provided a reliable means to break apart clods. The sweep and stirrup also operated deeper than the block. Soil moisture levels rise with increasing soil depth. As the block cultivator operated at the shallowest depth, this design took advantage of the fact that the soil surface moisture was lower. The block cultivator has the potential to operate

effectively over a wider range of soil moisture conditions compared to the other cultivators.   However, the effectiveness of the block in moist soil conditions may be a reflection of its capability to control the higher densities of weeds that often persist in moist soils, rather than a direct corollary to the soil moisture level itself.

Soil surface level was a unique attribute of the model which provided some explanatory power (Tables 2.2 and 2.3). Fewer weeds survived with the sweep, and to a lesser extent, with the block cultivator, when the soil surface was uneven at the time of cultivation (Figure 2.8). In contrast, stirrup cultivator efficacy was unaffected by differing degrees of soil surface levelness (Figure 2.8).

It is likely that soil surface level was not the primary variable responsible for these observed differences; rather, soil surface level could have been an indicator of the degree of soil compaction. Immediately after primary field activities occur (e.g.; by harrow, disk, or rototiller) cultivated soil is at its least compact, and the surface of this loosened soil is at its most uneven. The soil surface becomes more uniformly level, and the soil itself more compact, with both time (an effect known as age-hardening) and an increasing number of wet-to-dry cycles (rain events) (Dexter et al. 1988; Horn 1993; Horn and Dexter, 1989). S-tine sweep entry into the soil was inhibited by compaction; and to a lesser degree this physical response occurred with the block cultivator. The stirrup cultivator had a comparatively lower penetration resistance, and as such was less influenced by the degree of soil compression. However, no compaction data was collected to verify this
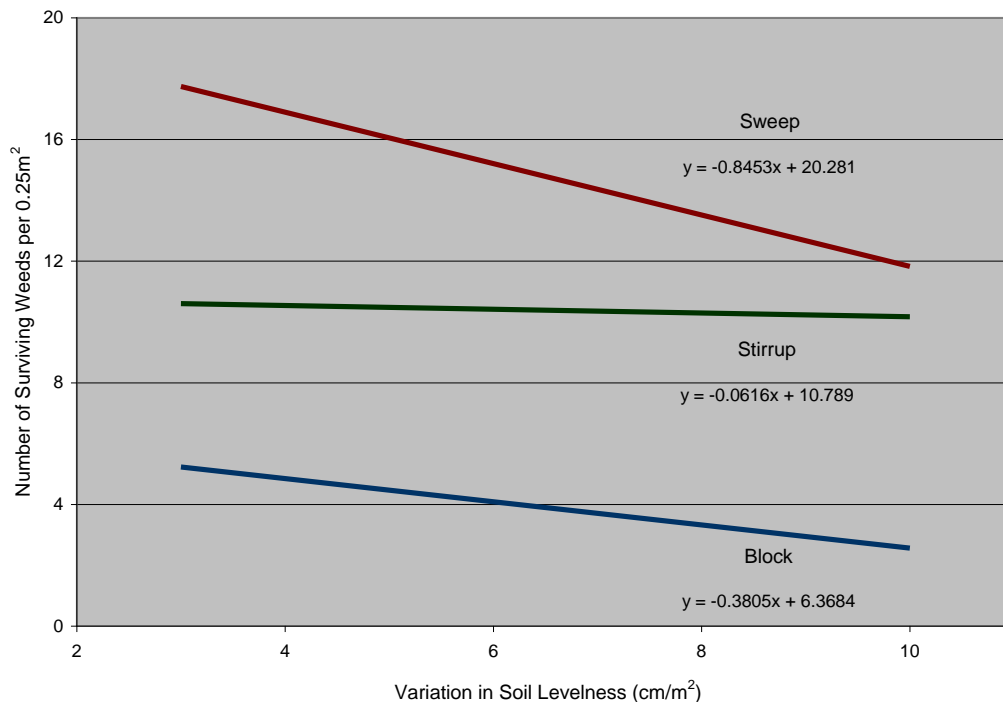
Figure 2.8. The influence of soil surface level and cultivator type on weed survival at one day after cultivation.

assessment. Mohler et al. (2000) found that weed control via mechanical cultivation was greater in a coarse seedbed treatment which was chiseled and disked, compared to a fine seedbed treatment which was chiseled, disked, and cultimulched. A cultimulcher increases soil compaction.

Soils that are high in clay, or low in organic matter, have a greater tendency towards compaction (Kooistra and Tovey 1994). A hardsetting soil has a structure which collapses after wetting, causing the soil to dry to a compacted mass (Dexter 2004; Mullins et al. 1987). Two features of hardsetting soils are a low organic matter content, and, a high content of sand and silt with only a small percentage of clay. Such soil is challenging to cultivate until it has been rewetted. In the two soil types in these experiments, the gravel loam, with its low organic matter and 13 to 16% clay content, had the greatest tendency to exhibit hardsetting. Thus, if compaction was a

negative factor in cultivator efficacy, we would expect poorer weed control with cultivations on the gravel loam soil relative to cultivations on the silt loam.

The proportion of weed survival, relative to the existing weed population, was influenced by the interaction between cultivator design and soil type (Table 2.2). With the sweep cultivator, and to some degree, the block cultivator, there were proportionally more weeds surviving in the ten trials conducted on gravel loam as compared to the ten trials conducted on silt loam (Figure 2.9). In contrast, weed survival percentages between stirrup cultivations on both soil types were identical. It is probable that soil compaction, as indicated by soil surface levelness and soil type, influenced each cultivator differently. Sweep performance was negatively influenced by increasing soil compaction, block performance was somewhat influenced, and the stirrup was largely unaffected.

Weed population parameters affected cultivator performance. With all three cultivators, weed ground cover at the time of cultivation was a strong predictor as to the number of weeds surviving one day after cultivation (Table 2.3). There was not, however, a strong relationship between cultivator performance and mean weed size. For the sweep and stirrup, the greater the number of weeds present, the greater the number of weeds that survived (Table 2.3). It would stand to reason that, if a cultivator routinely controlled 90% of the weeds present, that weed survival in an area of 1000 weeds (100) would be greater than that of a like area containing 100 weeds (10). Unlike the stirrup and sweep, performance of the block cultivator was not linked to weed population level (P=0.7594). With the block cultivator, the high control levels observed across all weed populations may have overshadowed any population effects.

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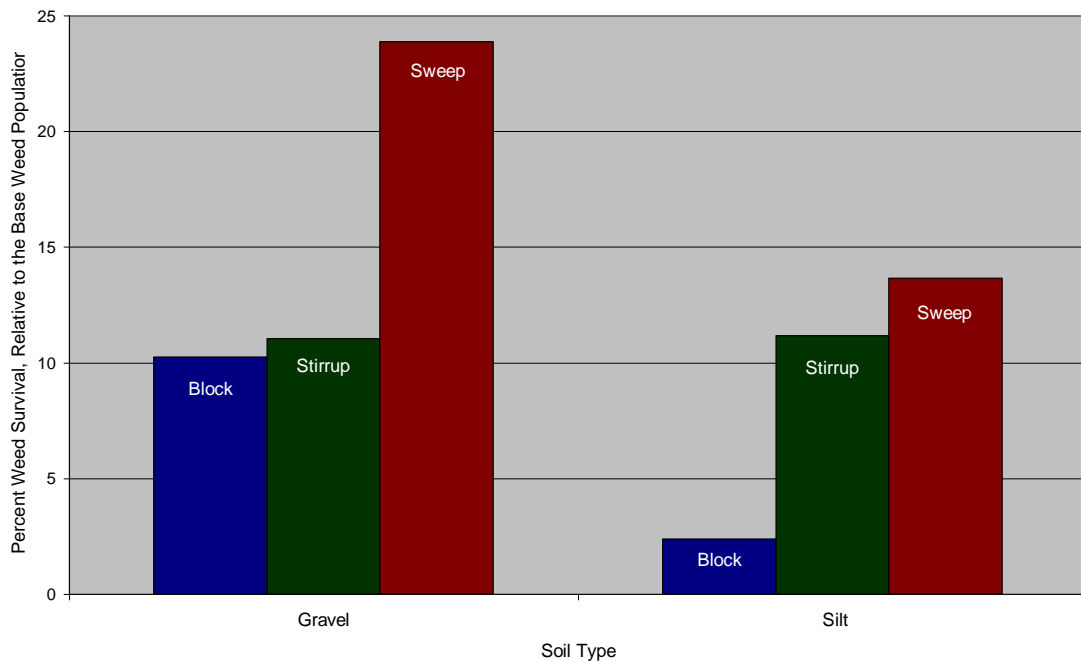
Figure 2.9. The proportion of surviving weeds in each soil type and with each cultivator (one day after cultivation), as a percentage of the base

The percent weed ground cover, assessed one day after cultivation via image analysis, reflects an interaction between weed size and weed density (Figure 2.10). With increasing weed densities and/or increasing weed size, there was more surface weed cover remaining post-cultivation. However, the strength of this relationship changed depending on which cultivator was being used. Sweep performance was the most dependent on weed population dynamics ($R^2 = 0.80$), whereas the block cultivator was the least dependent ($R^2 = 0.48$). Weed morphology, density, and size have all been reported to influence the efficacy of mechanical cultivation (Baerveldt and Ascard 1999; Bond et. al 2007; Rasmussen 1993). While weed population parameters influenced control with all three cultivators, the block cultivator was the least affected.
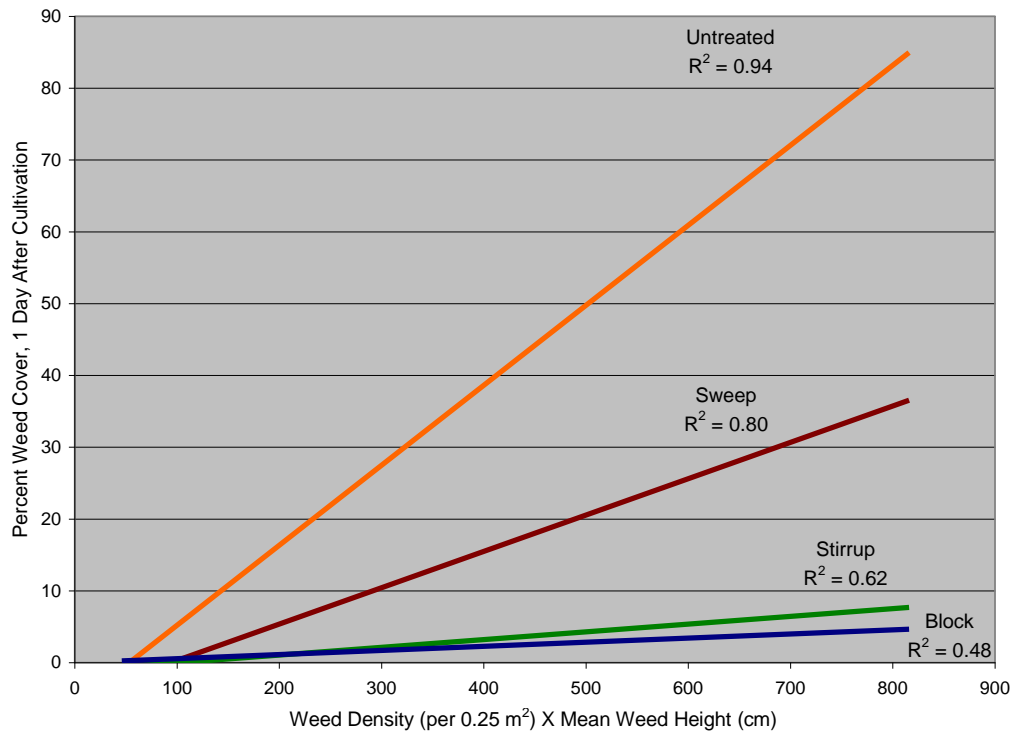
Figure 2.10. The impact of weed size and density on the percent of ground covered by weeds before and after cultivation.

The ability of each cultivator to control specific weed species was difficult to assess since no single species was present in all 20 trials. The most common weed species was hairy galinsoga, which was present in 13 of the 20 trials. Average post-cultivation survival of galinsoga was 9 weeds per 0.25 m^2 with the sweep cultivator, 7 with the stirrup, and 2 with the block. The range of variability in galinsoga survival also differed between tools. There were, on average, < 1 to 26 survivors per 0.25 m^2 with the sweep, < 1 to 21 survivors with the stirrup, and < 1 to 6 survivors with the block. With the block cultivator, galinsoga control increased, and the variability in the range of that control decreased, relative to the other tools.

Cultivator usefulness can be undermined by post-cultivation weed escapes, and by the potential stimulation of weed germination. The number of

weeds which appeared controlled at one day after cultivation, and yet regrew by 14 days after cultivation, averaged between one and two per 0.25 m^2 (Figure 2.11). There were no striking differences between cultivator designs, although weed escapes were generally fewer with the new designs.

All cultivation events have a tendency to trigger new weed germination (Milberg et al. 1996; Pons 1992). Implements can stimulate and redistribute weed seeds in different ways (Cousens and Moss 1990). Grundy and Bond (1998) found that spring tines tended to bring seed to the surface, whereas a rototiller tended to push seeds deeper into the soil profile. In these experiments, there were no significant differences in new weed germination (at 14 days after cultivation) between the three tested implements (Figure 2.11).
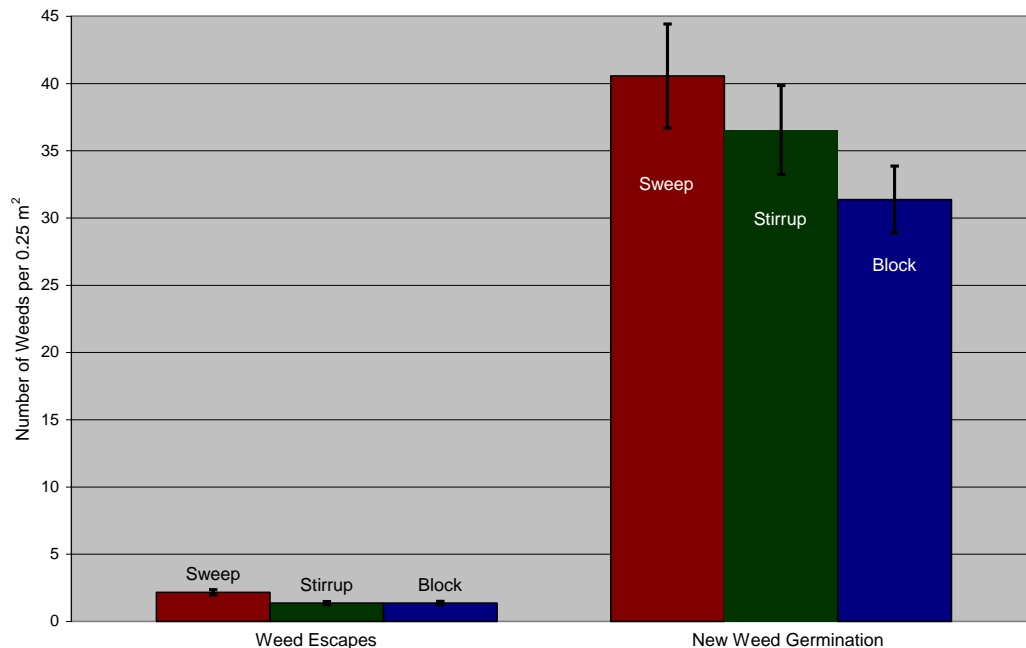

Figure 2.11 The number of escaped weeds and newly germinating weeds, by cultivator type, 14 days after cultivation. Standard error bars shown.

Most germinable weed seed lies in the upper few centimeters of the soil. Since all three cultivators disrupted this soil layer, the seeds were equally likely to germinate. With a single cultivation, it is unlikely that new weed germination will be influenced by the type of cultivator. However, with multiple cultivation passes across the same area, differences could appear. Soil disturbance with the block cultivator is shallower than that with the sweep or stirrup, and thus a smaller volume of soil is continually being disturbed. With frequent shallow cultivation, there is the potential that new seed germination could be exhausted sooner, as the available pool of germinable seed becomes smaller and smaller (Roberts and Dawkins 1967). This could be an important factor in field operations where multiple cultivations are made in a single season.

Weed mortality with each of the three cultivators was largely a result of burial (Figure 2.12). The success of this burial mechanism varied by cultivator; i.e., higher weed survival numbers with the sweep translated into a lower number of weeds killed by burial, and vice versa with the block. Slight increases in the number of weeds killed via desiccation were observed with the stirrup cultivator. This may reflect the slicing motion of the tool, whereby soil is disturbed, but less overturned, than with either the sweep or block. As a consequence, more weeds would remain at the surface, with soil separated from roots, and become subject to desiccation. Increased performance with the block and stirrup cultivators was not due to novel mechanisms of mortality, but instead, reflected increased tool tolerance to operational and environmental inconsistencies.

It is likely that, with weed burial in particular, the mortality of a given weed may be due to a combination of factors. For example, a weed that is

buried may also have sustained some degree of crushing of stems and leaves, and certainly had soil disturbance around the roots. These factors together would amplify the potential stress on a weed and minimize the likelihood of regrowth. Categorizing weed mortality by only the primary observable cause of weed death, as has been done in this research, limits interpretation of possible interactions between multiple mortality mechanisms.
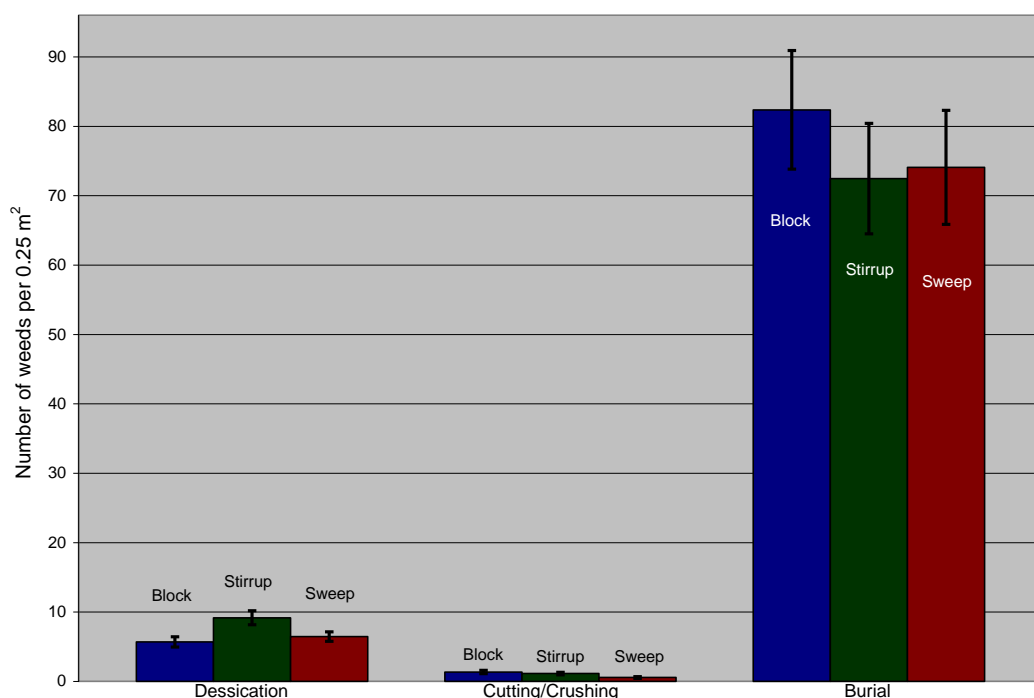
Figure 2.12 The distribution in the mechanisms of weed mortality with each of the three cultivators. Standard error bars shown.

Crop Response

Pepper and broccoli per-plant yields were comparable between plants cultivated with the new cultivator designs and those cultivated with the traditional S-tines (Figures 2.13 and 2.14). Plot yield and harvestable number of heads (broccoli) or peppers did not differ significantly between treatments
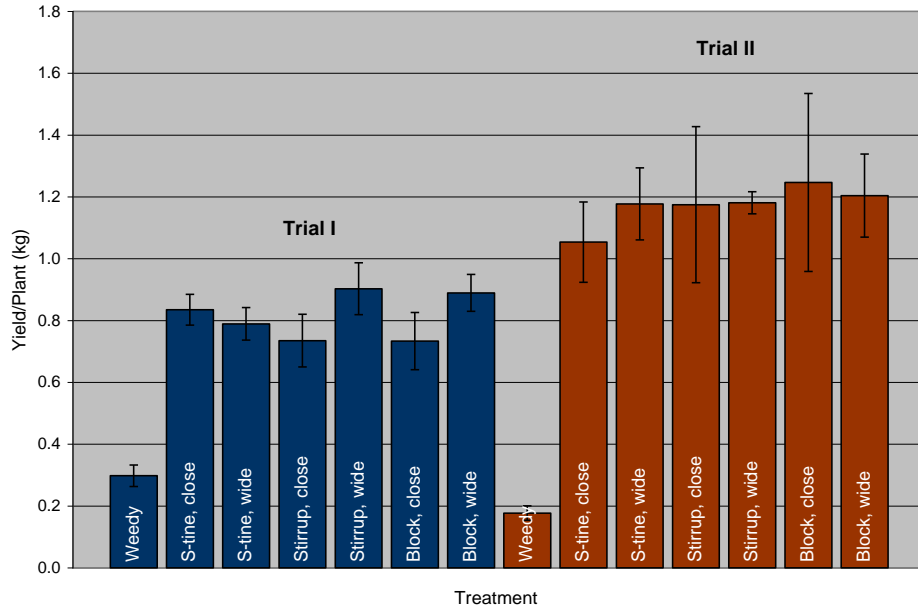
Figure 2.13. Pepper plant yield across cultivation treatments and trial locations. Standard error bars shown.
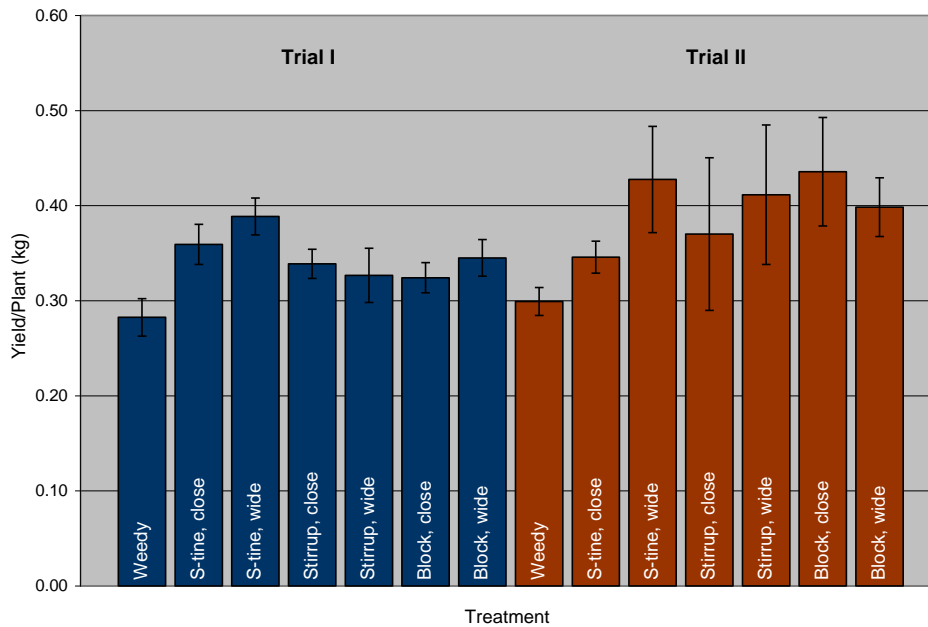
Figure 2.14 Broccoli per plant head weight across cultivation treatments and trial locations. Standard error bars shown.

(data not shown). Close cultivation appears possible with all three tools.
However, in some instances, particularly in pepper trial II, there was more
yield variability with close than with wide cultivations. With close cultivation
there was greater random occurrence of crop injury. Nevertheless, there was
little difference in crop response between the three tools.

The directionality of soil flow with each cultivator influenced soil
movement into the crop row. The flow-through passage of soil with the block
and stirrup cultivators limited soil movement sideways into crop rows. In
contrast, when the sweeps were operated at higher speeds, some soil was
"thrown" into the crop row. With tough crops, such as broccoli, beans, or
potato, soil movement into the crop row may be beneficial because it can bury
and suppress small intra-row weeds. However, more sensitive crops like
onion or carrot can be injured by this intra-row soil movement. In these trials,
pepper and broccoli plants were not noticeably affected.

Practical Considerations

Purchase costs bear consideration with each type of cultivator. A two-
row version of the tested sweep cultivator costs $1400.00. The cost for a two-
row version of the stirrup and block cultivators, based on the documented
prices of materials and estimated labor, would be $1300.00 and $1500.00
respectively.   It is likely that labor costs (time of production) would be reduced
within an efficient production system. Since both novel cultivators make use of
"shorts", small lengths of steel that are commonly sold as remnants of larger
pieces, there is also a potential for material savings.

Operational efficiency needs to be considered. McKyes and Maswaure
(1997) suggested that to minimize the draft requirement for a tillage tool, it

should be designed to operate at a shallow depth and with a low rake angle. Both the stirrup and block cultivators operate at shallower depths than typical sweep setups. Blade angle is less than 30° with both tools. However, field experiences indicate that the draft requirement of all three tools is relatively small, as each can be pulled at low engine revolutions and at high speeds with little difficulty.

Draft differences between the tested tools may not be particularly relevant, as compared to the more extreme differences in draft requirements between primary tillage implements like plows and harrows. Nevertheless, cultivations with the sweep, stirrup and block provide an energy savings relative to weed control with PTO-operated equipment (e.g. a brush hoe or rototiller), as these alternatives require a higher engine speed and a slower travel speed. Because the block and stirrup cultivators provide higher levels of weed control with a single operation, it is possible that fewer cultivations would be needed to provide season-long control. Reducing the number of cultivations, or the need for multiple passes within a single cultivation event, would reduce on-farm fuel usage and operator time.

Weed control with the three cultivation tools was strongly dependent on the capability of each tool within the tested range of travel speeds, weed pressures, and soil parameters. The S-tine sweep was highly influenced by environmental conditions and the speed of cultivation. As a result, overall performance was lowered. In contrast, the block cultivator was minimally impacted by variations in environmental conditions or working speed and weed control was consistently highest with this tool. The stirrup cultivator was intermediate between the block and sweep cultivators. There were no distinct differences between post-cultivation weed survival and new weed germination

with any of the tested tools. Additionally, each design had a similar purchase cost and draft requirement.

At the time of this writing, Cornell University has license rights to the stirrup and block designs. Integration of either tool into the mechanical marketplace is dependent on piquing the interest of agricultural tool manufacturers who see fit to invest in these designs. By producing cultivation tools that are functionally independent of the uncontrollable variables, operational and environmental, that occur in agriculture, we can increase the consistency and reliability of cultivation as a weed management technique. The block cultivator, due to increased flexibility, has the potential to significantly improve inter-row mechanical weed management.

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Chapter Three

The Integration of Vinegar for In-Row Weed Control

In Transplanted Bell Pepper and Broccoli

Abstract

Vinegar, an organic herbicide, can supplement the existing intra-row weed control options of organic farmers. However, there are two primary limitations to its use in vegetable crops. First, it is expensive. Second, vinegar applications that contact the crop can cause injury and yield loss. The aim of this research was to use vinegar to control intra-row weeds in bell pepper and broccoli in a way that product costs would be reduced and crop injury would be minimized. Vinegar was banded in-row to reduce product volume and expense. Applications were shielded and directed below the crop canopy to minimize contact with crop foliage. Stem protectants, organic paints applied to crop stems, were included and evaluated as potential physical barriers to crop stem injury. A tractor mounted sprayer/cultivator was constructed to apply a 25 cm-wide band of vinegar at the base of two crop rows, while the inter-row areas were simultaneously cultivated. Four field trials were conducted in 2009, two in transplanted bell pepper and two in transplanted broccoli. A single application of 200-grain vinegar (20% acetic acid) at 700 L/ha was applied when weeds were in the cotyledon to six-leaf stage. Applications were made to crops with the lower stems coated in one of two organic paints (linseed oil and clay-based) or left uncoated. Handweeded and weedy in-row treatments were included for comparison. One day after vinegar application, in-row weed control was 100% in both pepper trials, and greater than 96% in the broccoli trials. Two weeks after application, there were 75% fewer weeds germinating in the vinegar treated areas, as compared to the areas which were handweeded. With vinegar, there was minimal soil disturbance, so the potential to stimulate latent weed seed germination was significantly reduced. Neither stem paint prevented crop injury; the clay paint flaked off within 2

weeks while the linseed oil was phytotoxic. Despite pepper foliar injury of less than 5%, stem injury by 2 weeks post-application contributed to a measurable reduction in yield. Broccoli injury with vinegar was limited to instances where overspray contacted the crop canopy. Although per-plant broccoli yields were not significantly reduced, per-plot yields were reduced. With vinegar, high levels of weed control, and the extended duration of that control relative to handweeding, could facilitate improved organic intra-row weed control. However, crop injury must be reliably reduced beyond the levels found in these studies. More research will be needed to assess the value of alternative stem protectant materials.

Introduction

    Organic farmers need new methods to improve weed management within crop rows. The potential use of natural products has received substantial interest (Boyd and Brennan 2006; Daniels 2004; Ferguson 2004). Products which are made through natural processes and have herbicidal properties, are permissible for use in organic agriculture. Materials including vinegar, citric acid, and essential oils can supplement in-row handweeding, cultivation, plastics, and flame-weeding. However, successful integration of natural products for in-row weed control will require development of application technologies that can minimize crop injury and lower usage volumes. The focus of this research was to develop application strategies that could facilitate the use of vinegar for in-row weed control. Vinegar would then be evaluated as a direct substitute for intra-row hand weeding.

There are practical limitations to the use of vinegar in vegetable crops. Vinegar can be costly when broadcast at the rates necessary for adequate weed control. A broadcast application of unregistered vinegar[1] would cost 435 $/ha, and an application with a registered vinegar product[2] would cost four times more. Banding an application to target only in-row weeds would substantially reduce the volume of product used, while providing control where it is most needed. Vinegar is a non-selective product, working on contact to burn exposed plant parts (Teasdale 2002). Thus, contact with crops can cause injury and reduce yields. Directing applications below a crop canopy would minimize product contact with crop leaves. The addition of a physical barrier between crop stems and the vinegar spray could lower the potential for stem damage. By addressing both the cost and crop safety issues with vinegar, organic growers might gain a valuable option for in-row weed control.

Vinegar, when applied at an adequate concentration and volume, is capable of controlling small annual broadleaf weeds (Evans and Bellinder 2009; Evans et al. 2009; Abouziena et al. 2009). Vinegar provides maximal weed control around one day after application and has no residual activity. Field applications of 180-grain vinegar provided greater than 90% control of carpetweed (*Mullugo verticillata* L.), yellow woodsorrel (*Oxalis stricta* L.), common lambsquarters (*Chenopodium album* L.), smooth pigweed (*Amaranthus hybridus* L.), and velvetleaf (*Abutilon theophrasti* Medic) (Chandran 2003). Johnson et al. (2004) found that 100-grain vinegar, when

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[1] Vinegar, 200-grain white, Fleishmann's Vinegar Co., Inc., 12604 Hiddencreek Way, Suite A, Cerritos, CA 90703.

[2] WeedPharm, Pharm Solutions Inc., 2023 E. Sims Way, Suite 358, Port Townsend, WA 98368.

applied at 1600 L/ha, provided greater than 80% control of shepherd's purse (*Capsella bursa-pastoris* L. Medic.). Vinegar is less effective at controlling grasses than broadleaf weeds (Curran et al. 2003; Evans and Bellinder 2009; Forsberg 2004). Curran et al. (2003) found that applications of 200-grain vinegar applied at 279, 561, and 840 L/ha controlled giant foxtail (*Setaria faberi* Herrm.) and yellow foxtail (*Setaria pumila* Poir.) from 28% at 279 L/ha to 42% at 840 L/ha. Smooth pigweed control ranged from 47 to 90% over the different spray volumes, with increased control at higher volumes (Curran et al. 2003). In previous field research, 200-grain vinegar, applied at 636 L/ha, provided 91% control (one day after treatment) and a 93% biomass reduction (2 weeks after treatment) when the targeted weeds had 6 leaves or less (Evans and Bellinder 2009).

The use of vinegar in vegetable cropping systems has been considered. Studies to date have evaluated vinegar in potato (Chandran et al. 2003; Evans and Bellinder 2009), garlic (Forsberg 2004), pepper (Chandran 2003), onion (Evans and Bellinder 2009), soybean (Coffman et al. 2004) and corn (Coffman et al. 2005; Evans and Bellinder 2009; Radhakrishnan et al. 2003). In these studies, crop response to vinegar depended on crop size, innate vigor, and the degree of contact. Resilient crops, like potato and corn, may recover from early foliar injuries with vinegar (Boydston 2004; Evans and Bellinder 2009). Spray strategies which minimize crop contact will substantially reduce injury levels. Coffman et al. (2005) found that a basal spray of 200-grain vinegar on sweet corn, applied to the point of runoff, resulted in less than 5% injury.

In order to apply vinegar as a banded directed spray, low-cost application equipment needs to be available or readily constructible. Banded

herbicide technologies exist for conventional growers, but need to be adapted for effective vinegar use. The corrosive nature of vinegar, as well as other natural products, demands that sprayers designed for use with these products be built with corrosion-resistant parts (Anon 2008). Many organic growers have limited equipment for banding herbicides and would need to acquire or build an efficient delivery system before adopting the technology. Adding a banded herbicide sprayer to existing cultivation equipment would make sense because most organic farmers already make extensive use of between-row cultivation, and the optimal timing of vinegar applications corresponds to optimal cultivation timings. By "piggy-backing" in-row vinegar applications on between-row cultivation operations, labor and energy costs for weed control would be minimized.

With broadcast vinegar applications, crop foliage intercepts the largest portion of the spray, and subsequently is most prone to damage. Although a spray directed beneath the crop canopy will minimize foliar contact, vinegar will still contact the crop stem. One potential method for avoiding stem injury is the use of a physical barrier (i.e. a stem protectant) on the crop stem to prevent or reduce the degree of vinegar contact. Stem protectants, in the form of wrappings on young fruit trees, have been used in orchards to mitigate herbicide damage and injury from herbivores (Agnello and Breth 2009). The use of stem protectants in vegetable cropping systems has not been reported. Organic paints are products sold for residential painting which are made with natural ingredients (e.g. linseed oil, clays, and milk). When these paints are applied to crop stems prior to a vinegar application they may provide a barrier to stem injury, without violating organic standards. Crop tolerance and effectiveness of individual stem protectants would need to be considered.

Vinegar may have value for in-row weed control in bell pepper and broccoli. Both pepper and broccoli have tough stems and an upright architecture, which might minimize product injury to the stems of these plants and make it possible to direct a spray below the crop canopy. Direct injury to the harvested parts of pepper and broccoli would not be an issue, as these portions mature well after the last possible application timing. Applications to pepper could shift an emphasis away from the extensive use of black plastic, which is expensive and a source of environmental contamination (Brown and Channell-Butcher 2001; Hochmuth 1998; Lamont 1993; Rice et al. 2001). Each year, conventional pepper growers can spend from 500 to 1,100 $/ha on weed management (Klonsky et al. 1997; VanSickle et al. 2007). Cultivation and handweeding row middles between pepper grown on plastic can cost 1,900 $/ha (Anon. 2006). The high crop return with organic pepper might justify several banded applications of vinegar. Weed control in broccoli, which matures from transplant in 45 to 60 days, could potentially be obtained with a single vinegar application. Vinegar applicability in broccoli could be extended to other crucifer crops (e.g. brussel sprouts, cauliflower, and cabbage).

The objectives of this research were: to design and construct a banded sprayer that could accurately direct vinegar to the base of a transplanted crop; to assess the in-row weed control potential of 200-grain vinegar relative to in-row handweeding; to determine the response of transplanted bell pepper and broccoli to vinegar; and, to evaluate two different organic stem paints for their potential to prevent crop stem injury.

Materials and Methods

Banded Sprayer Design and Construction

A sprayer was designed and constructed that would direct a 25 cm wide spray band, centered beneath each of two crop rows (Figures 3.1 and 3.2). Half of the spray width (12.5 cm) was delivered by one nozzle on one side of the crop row, and the other half by a second nozzle on the other side of the crop row. This sprayer was a revision of an earlier design that was constructed and trialed in 2007 (Appendix, Figures A.1 and A.2). The completed sprayer was mounted to the rear of a cultivator toolbar so cultivation between crop rows, and banding of vinegar within crop rows could be done concurrently. Inter-row cultivation occurred with the block and stirrup tools discussed in Chapter 2.

Materials, including stainless steel, EPDM (ethylene propylene diene Monomer (M-class) rubber), polypropylene, and CPVC (chlorinated polyvinyl chloride) were incorporated into the sprayer, as these materials are the most chemically-resistant to high-strength vinegar (Anon. 2007). The tool was constructed using basic welding and metal-fabrication techniques. Pressurized CO_2 was used as a propellant for the system. A solenoid valve was wired off of the tractor battery to provide the operator with a direct means of turning the sprayer on and off. Total cost was calculated for construction of the tool.

Several features make this banded sprayer unique (Figures 3.1 and 3.2). The sprayer is attached to the cultivator toolbar via two parallel points, with flexible circular connections at each end (Figure 3.1). This design allows the sprayer frame to move up and down during operation, rather than remain held in a single fixed position. The sprayer can also be raised, and held in a

Figure 3.1. Images of the banded directed sprayer. Clockwise from the top: side view of sprayer (black) mounted to the rear of an inter-row cultivator (blue) with pivot points (A) and height-adjustable wheels (B); side view of sprayer raised in transport position with CO_2 pressure tank and vinegar holding tank (C); close-up of spray shield shape and orientation.

Figure 3.2. Images of the banded directed sprayer in action. Top: vinegar application in two 25-cm wide bands, with areas in-between cultivated; bottom: close-up of shields lifting broccoli leaves up and over the spray nozzles, while exposing weeds around the plant base.

storage position, when use of only the cultivator is needed (Figure 3.1). Two height-adjustable wheels were mounted to the rear of the sprayer (Figure 3.1). Adjustments in wheel height alter spray nozzle height. The combination of a single flexible pivot point, coupled to rear wheels, enables sprayer height relative to the ground to remain constant, despite unevenness in cultivator depth or the field surface.

Specialized shields over each spray nozzle reduce drift and off-target spray movement (Figure 3.1). The shape of these shields, flat on the front, then rising over the nozzles and declining again in the rear, helps to push low crop leaves up and away from the spray path (Figure 3.2). This decreases the incidence of leaf damage and increases spray penetration beneath the crop canopy. By angling each shield down in the front, a greater number of lower leaves are forced to move over the spray nozzles (Figure 3.2). Additionally, this shield orientation protects spray nozzles from stones or random soil surface debris. Nozzle bodies with adjustable angles were used to provide flexibility in the orientation and angle of the spray pattern (Figure 3.2). Stainless steel even flat fan spray tips[3] provided uniform coverage of the in-row area and durability to repeated contact with vinegar. Placement of the sprayer aft of the cultivator prevented cultivation equipment from coming into constant contact with the vinegar.

Pepper and Broccoli Field Trials

Field trials were conducted in the summer of 2009 at the H. C. Thompson Vegetable Research Farm in Freeville, NY. Trials in transplanted

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[3] Teejet 8002EVS spray nozzle, Teejet Spraying Systems Co., P.O.Box 7900, Wheaton, IL 60189-7900.

bell pepper 'Lady Bell' and broccoli 'Premium Crop' were each conducted twice in different fields. Soil in all fields was a Howard gravel loam (HGL[3]; loamy-skeletal mixed mesic Glossoboric Hapludalf). All fields were moldboard plowed, disked, fertilized, and field cultivated prior to transplanting.

Two days before transplanting, the bottom 12 cm of broccoli and pepper stems were coated in one of two organic paints, a linseed oil[4] or a clay based product[5], or left uncoated. Paints were manually applied with a small bristle brush. Plants were then mechanically transplanted 60 cm apart, in rows spaced 76 cm apart. Each plot was 1.5 m-wide and contained two, 7.6 m-long crop rows. Trials were randomized complete block designs with four replications.

A single application of 200-grain vinegar, at 700 L/ha, was applied to plants with each stem protectant, and to those without. The 25 cm band of vinegar was centered at the base of each crop row, and directed beneath the crop canopy. Applications were made at a 2 km/hr travel speed. Additional treatments were included where stem paints were applied to the crops, and the in-row area kept weed free with handweeding and hand hoeing. These treatments were to assess potential paint phytotoxicity. Handweeded and weedy in-row treatments, both without stem paint, were also included for comparison. Block and stirrup cultivation tools (Chapter 2) were used to control weeds in the inter-row area of all treatments.

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[4] Allback Organic Linseed Oil Paint, Viking Sales Inc., 7710 Victor-Mendon Rd., Victor NY 14564

[5] Green Planet Paints: Interior Eggshell Sorrel, Green Planet Paints, 9413 N. Central Ave., Phoenix AZ 85020

Both broccoli trials were planted on May 20th, cultivated 16 days after planting (DAP), and sprayed and cultivated at 26 DAP. Broccoli was then harvested 51 DAP. Pepper trials were planted on June 1st, sprayed and cultivated 14 DAP, and then cultivated again 38 and 46 DAP. Peppers were harvested at 65, 72, and 82 DAP. Broccoli was 30 cm tall at the time of vinegar application, and pepper was at the 8 leaf stage (20 cm tall). Targeted weeds were in the cotyledon to six-leaf stage and included (in order of prevalence) hairy galinsoga (*Galinsoga quadriradiata Cav.*), common lambsquarters (*Chenopodium album* L.), redroot pigweed (*Amaranthus retroflexus* L.), large crabgrass (*Digitaria sanguinalis* L. Scop.), and shepherd's-purse (*Capsella bursa-pastoris* L. Medic.).

A permanent 0.25 m^2 quadrat was established in the center of each crop row in each plot (two per plot) one day after vinegar had been applied. The number of surviving weeds were counted in each quadrat. These weeds were then cut at their base and discarded. Quadrats were revisited two weeks later and counts were taken of emerged weeds. In-row weed counts in the handweeded-only treatments were done in an identical manner at one day and two weeks after the first handweeding. The initial handweeding in the handweeded treatments occurred on the same day as the vinegar application. Crop injury and yield data were collected for all treatments. With exception of the weedy check, all treatments were kept weed-free until harvest. Handweeding events were timed in each treatment.

All data were subjected to ANOVA. The PROC MIXED procedure in SAS statistical software[6] was used to assess the main effects of stem

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[6] SAS 9.2. SAS Institute Inc, 100 SAS Campus Drive, Cary NC 27513

treatment, crop type, and the presence or absence of vinegar, for their influence on yield relative to the handweeded control. Fisher's protected LSD tests were conducted to compare selected treatments, with significance values set at P≤0.05.

Results and Discussion

Weed Control

Vinegar provided a high level of weed control one day after application (Table 3.1). Control in the vinegar treatment did not significantly differ from that in the handweeded treatment. There was 100% weed control in both pepper trials, and greater than 96% control in the broccoli trials. Weeds were in the cotyledon to six-leaf stage at the time of application. Research has shown that targeting weeds at these smaller sizes will maximize control (Abouziena et al. 2009; Evans and Bellinder 2009; Evans et al. 2009). Slight reductions in control in the broccoli trial were partially due to the higher numbers of weeds present in these trials. The broccoli plants were also larger than the pepper plants at the time of application. Vinegar which contacted lower broccoli leaves was unable to affect the weeds directly behind or beneath these leaves.

The duration of control is important. Since vinegar does not have residual activity, control will not persist over the long-term. In this study, vinegar reduced post application weed germination relative to in-row treatments which were handweeded and hand-hoed (Figure 3.3). Data from earlier trials conducted in 2007 in pepper and brussel sprouts supports these findings (Appendix). Because vinegar applications did not disturb the soil,

Table 3.1. Weed survival in pepper and broccoli trials one day after in-row handweeding or vinegar application[a].

Treatment	Pepper		Broccoli		Mean of all Trials
	Trial I	Trial II	Trial I	Trial II	
	-----Number of weeds per 0.25 m^2, 1 day post-treatment-----				
Weedy	10 a	34 a	69 a	158 a	68 a
Handweeded	0 b	0 b	0 b	0 b	0 b
Vinegar 700 L/ha	0 b	0 b	1 b	6 b	2 b

[a] Within each column, means followed by different letters were significantly different (P≤0.05, LSD).
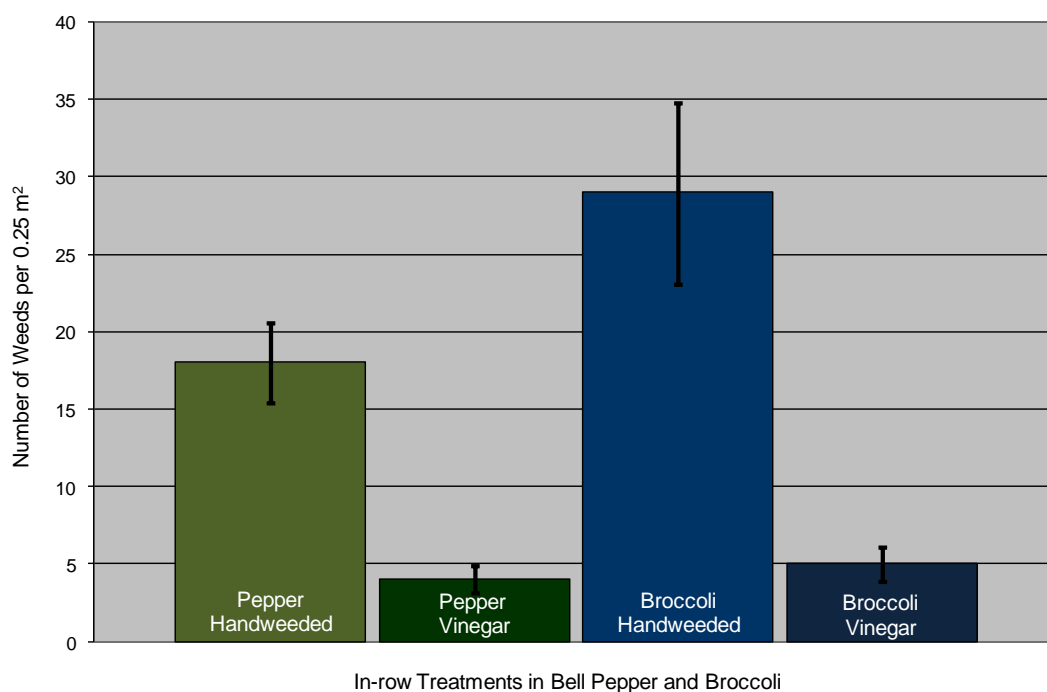

Figure 3.3. In-row weed counts in pepper and broccoli 2 weeks after vinegar applications or handweeding had occurred (data combined across trials). Standard error bars are shown.

fewer weed seeds were exposed to light or otherwise stimulated to germinate. Thus, the duration of in-row weed suppression will be longer when vinegar is used rather than cultivation or handweeding.

The directed band applications of vinegar reduced the need for supplemental handweeding. Time spent handweeding, extrapolated to hours/ha, is shown in Table 3.2. In these trials, handweeding a hectare of pepper or broccoli required an average of 169 hours of labor. Lanini and Le Strange (1994) found that season-long weed control of a hectare of pepper required 200 or more hours of handweeding. Similarly, Gianessi and Reigner (2007) reported that handweeding a hectare of hot pepper took 149 hours. Relative to the handweeded-only treatments, the vinegar treatments provided identical weed control with an 85% reduction in time spent weeding (averaged across all four trials).

Treatment differences in handweeding times translated into differences in weed management costs. If handweeding costs are averaged at $7/hr, then the integration of vinegar for in-row weed control would reduce handweeding

Table 3.2. The duration of intra-row handweeding in the handweeded and vinegar treatments of each pepper and broccoli trial[a].

Treatment	Pepper		Broccoli		Mean of all Trials
	Trial I	Trial II	Trial I	Trial II	
	-----Time of intra-row handweeding (hr/ha)-----				
Handweeded	175 a	158 a	174 a	168 a	169 a
Vinegar 700 L/ha	50 b	50 b	0 b	0 b	25 b

[a] Within each column, means followed by different letters were significantly different (P≤0.05, LSD).

expenses from over $1000/ha to around $175/ha. The in-row vinegar application would cost an additional 145 to 580 $/ha, depending on the source of product. There is also the purchase cost of the sprayer to consider. The sprayer used in these trials was built for around $400. There may be a cost-justification to in-row applications of vinegar, with the important stipulation that crop yield is not reduced.

Crop Response

Crop response to vinegar, without stem protection, was dependent on two factors: the successful integration of the spray system to accurately direct the spray below the crop canopy; and, the inherent resistance of the crop to injury. With pepper, initial post-application tolerance to vinegar was excellent, with less than 5% injury one day after treatment (DAT; data not shown). However, scarring of the stems contributed to a delayed injury response; by two weeks after treatment a significant portion of the treated pepper plants had fallen over or broken off at their base (Figure 3.4). These responses were due to a physical weakening of the lower plant stems (Figure 3.4).

Broccoli stems were not notably impacted by the vinegar application, and an equivalent numbers of plants remained upright in the vinegar treated and untreated plots. A trial in brussel sprouts in 2007 found identical levels of stem tolerance for this Brassica species (Appendix). Relative to pepper, broccoli plants were larger and wider at the time of the vinegar application. This contributed to increased spray contact with foliage, with 16% foliar necrosis 2 DAT. Tillett et al. (2008) noted that Brassica plants do not grow vertically from their root system; the center of their foliage is offset from the

Figure 3.4. Application of 200-grain vinegar (700 L/ha) on pepper. Top: plot photos were taken 2 (left) and 14 (right) days after application. Many plants had fallen over by 14 days after application. Bottom: lower stem injury due to contact with the vinegar (note flaking of the clay-based stem paint).

root mass. This growth habit made minimizing foliar contact with vinegar difficult as the plants were not evenly aligned within the row. An earlier application may have been less injurious, as the plants would have been smaller and their foliar orientation more uniform. Incorporation of a row-guided sprayer system that could track and adjust spray nozzles to center over crop plants would further increase application precision (Slaughter et al. 2007).

Yields of broccoli and pepper were reduced with vinegar applications, regardless of whether stem paints were included (Figures 3.5 and 3.6). Within a main effects multivariable model, crop type, stem treatment, and the presence or absence of vinegar all significantly influenced (P≤0.03) the level at which yields were reduced relative to the handweeded control. Of the two crops, broccoli was the most tolerant to vinegar, though per-plot yields were still lowered by around 15 to 20% relative to the handweeded control. Per-plant broccoli yields were not significantly reduced from the handweeded treatment (data not shown).

The negative yield response in both crops was due to crop injury, and not weed competition. Broccoli injury with vinegar applications was limited to instances where overspray contacted the crop canopy. Coffman et al. (2007) found similar yield reductions, between 25 and 30%, when 200-grain vinegar was applied to the base of broccoli to the point of runoff. However, in their trial, broccoli plants and weeds were greater than 50 cm tall, which contributed to excessive lower leaf damage and poor weed control. In this trial, yield reductions were primarily a response to upper leaf damage from the random instances when sprayer alignment was skewed to the broccoli row. Had sprayer alignment been improved, or crop canopy size smaller at the time of application, it is probable that significant yield reductions would not have been
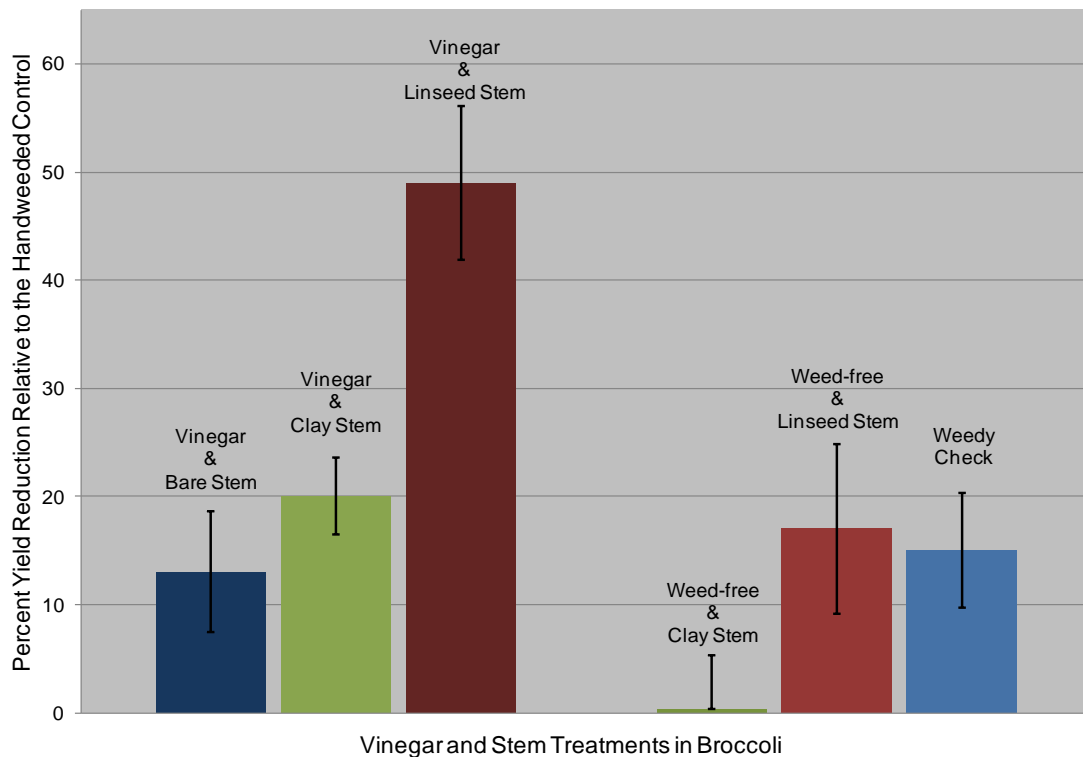
Figure 3.5. The percent yield reduction of broccoli, relative to the handweeded control, in treatments where vinegar was applied with and without a stem protectant, and where stem protectants were applied alone. Data was combined across trials. Standard error bars are shown.

observed. Yield of brussel sprouts treated in-row with vinegar in 2007 was not significantly different than that of a handweeded control (Appendix, Table A.3). The longer growing season and smaller size of the brussel sprout at the time of application likely contributed to this finding.

Pepper yields were measurably reduced with vinegar applications (Figure 3.6). Stem injuries contributed to over a 50% reduction in per plot yields (Figure 3.6). Per-plant yields, and the total number of harvestable peppers, were likewise reduced (data not shown). Similar results were found in a 2007 pepper trial (Appendix, Table A.2). Feasible integration of vinegar in pepper will require protection or shielding of the stem.
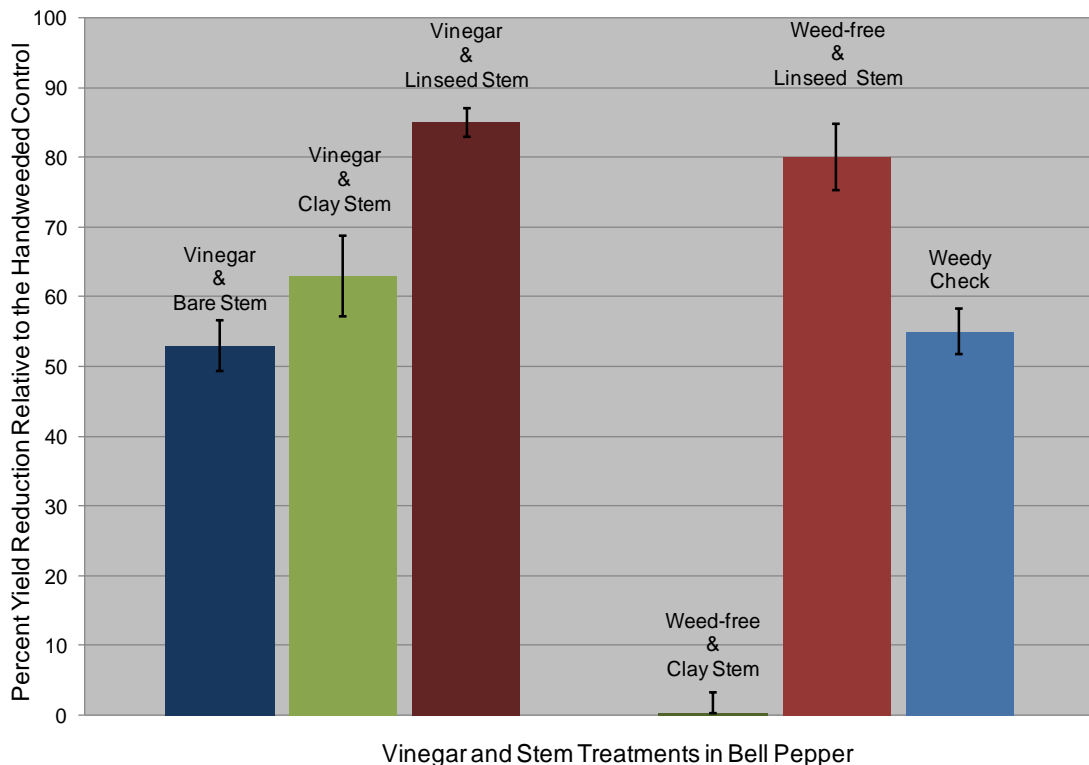
Figure 3.6. The percent yield reduction of bell pepper, relative to the handweeded control, in treatments where vinegar was applied with and without a stem protectant, and where stem protectants were applied alone. Data was combined across trials. Standard error bars are shown.

In both pepper and broccoli, yield reductions with vinegar were not significantly different than those found in the weedy checks; thus, there was no yield advantage to including vinegar (Figure 3.5 and 3.6). Coffman et al. (2004) found less than 5% injury of sweet corn and soybean when 200-grain vinegar was applied at their base to the point of runoff. It is possible that other crops may have more innate tolerance to basal vinegar applications. Decreasing the vinegar application volume and/or concentration may lessen crop injury, although weed control might also be reduced.

Stem Protectants

Both stem protectants failed to prevent crop injury. The clay paint flaked off by the time of application (2 weeks after painting). Therefore, stem injury was not prevented. The addition of the clay paint alone, without vinegar, did not impact crop yield (Figures 3.5 and 3.6). The linseed oil protectant formed a longer lasting stem coating; however, the paint was phytotoxic to both pepper and broccoli. This resulted in significant yield loss when the linseed oil was applied without vinegar, and amplified yield loss when it was applied with vinegar (Figures 3.5 and 3.6). Neither of the tested organic paints show promise as stem protectants. However, unreplicated greenhouse trials using a conventional latex paint[7] as a stem protectant in pepper have shown potential (Figure 3.7).

Future work will evaluate directed sprays of vinegar along with alternate stem protectants, in the hopes of providing a longer-term physical barrier without phytotoxic effects. One possible organic barrier is the stem of Japanese knotweed (*Polygonum cuspidatum*). These stems are hollow, and short sections could be slipped around the lower stems of transplants, including pepper, much like trunk guards are used on fruit trees. The protectors would naturally decompose and would not require removal from the field. By coupling a viable stem protectant with the application strategies used in this research, crop safety of sensitive crops may be achievable. If successful, such techniques could facilitate the use of additional organic and conventional contact (e.g. paraquat in pepper) or foliar/stem absorbed herbicides in crops, which if treated otherwise, would be injured.

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[7] Valspar Premium Exterior Latex, Semigloss, Sawyer White, 1191 Wheeling Rd., Wheeling IL 60090.

Figure 3.7. Peppers 2 weeks after a basal application of 200-grain vinegar at 700 L/ha. Top: plant stems painted with a white latex paint. Bottom: plants with stems unprotected; foliage was uninjured but stem strength was compromised.

The cost of purchasing and applying a stem protectant needs to be considered. In this research, hand painting of crop stems would take 30 hours/ha, considering the crop spacing that was used in these trials. The cost of the paints was between 40 and 65 $/ha. An automated application of such paints would measurably decrease labor time and expense. Alternative

stem protectants, like the Japanese knotweed stem sections, could be acquired with limited expense (time to harvest, cut and install stem sections wound need to be considered) and would have no product labeling concerns. Compared to the cost of handweeding, the expenses of a stem protectant and a vinegar application may be justifiable. But, for this integrated system to be financially viable, crop stem and foliar injury must be reduced below the point at which yields are impacted.

Vinegar may have potential for in-row weed control. High levels of initial control, and the duration of that control, indicate that there is merit to using vinegar in-row relative to handweeding or hoeing. However, for vinegar to be feasibly integrated in vegetable cropping systems, crop injury must be reliably reduced beyond the levels found in these studies. Using a directed sprayer, like the one trialed, will lessen foliar injury. Nevertheless, stem injury remains a critical concern, particularly with sensitive crops like pepper. Stem protectant materials may aid in physically shielding crop stems, but more research on alternate products will be needed.

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APPENDIX

The Potential Use of Vinegar as a Banded Application Directed at the

Base of Transplanted Pepper and Brussel Sprouts

2007 Project Objectives:

1) Design, build and evaluate a low-cost, banded-herbicide sprayer that could be mounted on a between-row cultivator for integrated management of weeds in pepper and brussel sprouts.

2) Test the crop safety and weed suppression of vinegar sprayed at the base of transplanted pepper and brussel sprouts.

Summary

Field trials were conducted in 2007 using 200-grain vinegar (20% acetic acid), at 636 L/ha, in transplanted bell peppers and brussel sprouts. Treatments were applied as 25 cm wide bands, directed beneath the crop canopy. Applications were made with a customized tractor-mounted sprayer, with nozzles oriented below, and to each side, of the crop canopy. This sprayer was fixed onto an S-tine cultivator to allow for simultaneous in-row spraying and between-row cultivation. Vinegar treatments were compared to between-row cultivation (weedy in-row), between-row cultivation with in-row handweeding, and a weedy check (Table A.1).

Table A.1. Treatments in 2007 field trials.

Treatment	In-row Practice	Between-Row Practice
Weedy Check	None	None
Weedy in-row, and S-tine cultivated between-row	None	Multiple s-tine cultivations, each time the mean weed size reaches 2-leaves
Weedy in-row, and S-tine cultivated between-row	None	Multiple s-tine cultivations, each time the mean weed size reaches 4-leaves
Handweeded in row, and cultivated between-row	Repeated handweeding, each time the mean weed size reaches 2-leaves	Multiple s-tine cultivations, each time the mean weed size reaches 2-leaves
Handweeded in row, and cultivated between-row	Repeated handweeding, each time the mean weed size reaches 4-leaves	Multiple s-tine cultivations, each time the mean weed size reaches 4-leaves
Banded 200-grain vinegar, 636 L/ha + between-row cultivation	Multiple vinegar applications, each time the mean weed size reaches 2-leaves	Multiple s-tine cultivations, each time the mean weed size reaches 2-leaves
Banded 200-grain vinegar, 636 L/ha + between-row cultivation	Multiple vinegar applications, each time the mean weed size reaches 4-leaves	Multiple s-tine cultivations, each time the mean weed size reaches 4-leaves

Banded Herbicide Tool

Construction of the sprayer was completed for less than $375, with the exclusion of the cost of a holding tank and a pressure source. These items, and their cost, would vary widely depending on a given farmer's need for product volume and their current farm equipment. The tool effectively mounted on an existing cultivator. The sprayer bar was placed behind the cultivator, and the cultivator was mounted on the three-point hitch behind the

tractor. Overspray of the vinegar had minimal-to-no contact with either the tractor or the cultivator. In the course of the year, the sprayer components showed little wear; however the sprayer was always cleaned after each use.

The sprayer design is shown in Figures A.1 and A.2. Vinegar is directed to nozzles on each side of a given row. Under-leaf banded spray tips angle the vinegar under a crop canopy, essentially limiting spray contact to only the lowest leaf surfaces and stem. The shaft to which each nozzle body was attached was threaded on the upper 50 cm, allowing for adjustment of nozzle height relative to the depth of the cultivator. The nozzle bodies incorporated in the sprayer are double nozzle bodies, such that there are two available spray ports on each side of a given row. During the course of this experiment, only one nozzle on each side was utilized. Should the speed of the cultivation/spray application be increased, the additional spray nozzle on each side could be engaged to ensure application of a high enough volume of vinegar.

The sprayer assembly could benefit from the addition of spray shields, hoods that enclose each nozzle tip, deflecting spray contact from the crop. Such shielding would reduce the injury seen on pepper stems and further limit product contact on lower leaf surfaces.   Shields would need to be designed with a sloping surface that allows for the lower leaves of the crop to be gradually lifted as the hoods pass beneath the crop canopy. Shields may also reduce off-target changes in the vinegar spray pattern by deflecting wind interference.

Figure A.1. Rear view of the sprayer. Sprayer structure is in green; the existing cultivator is in red.
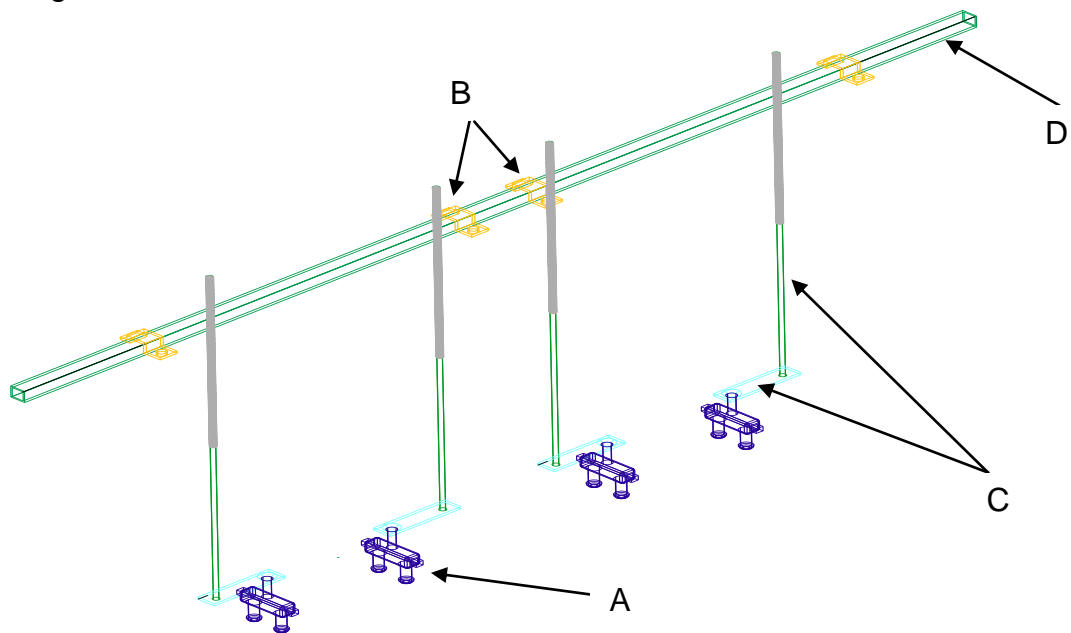

Figure A.2. An illustration of the sprayer structure, showing nozzle bodies (A), hose supports (B), adjustable rods/feet (C), and frame (D).

Field Trial in Pepper

Vinegar applications were made to peppers 'Ace' and 'Lipstick' either 27 or 33 days after transplanting. Weeds in the early and late treatments were, on average, at the 2-leaf or the 4-leaf stage, respectively. Initial injuries to the peppers 2 days after treatment (DAT) were slight (6 to 7% injury) and included lower leaf dieback and scarring of the stem. However, by 29 DAT, the early injury to the stem facilitated a basal rot and subsequent death of a number of pepper plants. By the time of harvest, the number of pepper plants of the variety 'Ace' had decreased by 14% and 'Lipstick' survival was decreased by 58%. Tolerances to vinegar will vary between pepper varieties.

Pepper injury and plant death contributed to yield losses in both vinegar treatments (Table A.2). Yields of 'Ace' were consistently greater than the weedy controls, but were lower than the handweeded treatments. With 'Ace', the mean yields per plant in the vinegar treatments were close to those of the handweeded controls. Pepper 'Lipstick' yield was further reduced relative to 'Ace'. The use of vinegar as a directed, banded application in pepper will require shielding of the vinegar away from the crop stems. Selecting tougher-stemmed, taller, varieties of pepper would further facilitate the use of vinegar. An alternative solution to limiting stem damage would be to encircle the pepper stems with short lengths of tubing or a wrapping of tape. These materials could provide a physical barrier to vinegar contact on the stem.

Application of 200-grain vinegar (636 L/ha) when weeds were at the 2-leaf stage reduced the number of in-row weeds by 88% (2 DAT), compared to the weedy in-row treatment. Application of vinegar when weeds were at 4-leaves reduced the number of in-row weeds by 73% (2 DAT). Although the differences in weed reductions between the two treatments were not

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significant (P≤0.10), weed control may be maximized when weeds are targeted at a younger growth stage. By 15 DAT, the number of weeds in the early vinegar-in-pepper treatment was still 82% less than the weedy check. In comparison, 15 days after weeding the handweeded pepper treatment, there remained only a 46% reduction in the number of in-row weeds. Light promotes germination of many weed species. Because vinegar applications did not disturb the soil in-row, less new weed seeds were exposed to light or brought into the upper soil surface. Thus, less new weeds were stimulated to germinate following a vinegar application relative to a weeding event which involved disturbance of the soil.

Table A.2. The mean marketable yield of pepper 'Ace' and 'Lipstick'.

Treatment	Pepper 'Ace'		Pepper 'Lipstick'	
	Yield/ Plot (KG)	Yield/ Plant (KG)	Yield/ Plot (KG)	Yield/ Plant (KG)
Weedy Check	8 d	0.73 d	4 bcd	0.38 c
Weedy In-Row Cultivation Between-Row, 2-lf	11 bcd	0.99 d	7 b	0.58 bc
Weedy In-Row Cultivation Between-Row, 4-lf	10 cd	0.88 d	6 bc	0.55 bc
Handweeded In-Row, 2-lf Cultivation Between-Row, 2-lf	22 a	1.84 ab	13 a	1.13 a
Handweeded In-Row, 4-lf Cultivation Between-Row, 4-lf	24 a	1.93 a	14 a	1.16 a
200-Grain Vinegar In-Row, 2-lf Cultivation Between-Row, 2-lf	13 bc	1.53 bc	2 d	0.64 b
200-Grain Vinegar In-Row, 4-lf Cultivation Between-Row, 4-lf	15 b	1.49 c	4 cd	0.62 bc

[a] Within columns, means of harvest data followed by the same letter were not significantly different (P≤0.10, Fisher's Protected LSD).

As the vinegar treatments did not require handweeding early in the season, 3 to 4 minutes of handweeding per 12 m^2 was eliminated with the use of vinegar. The use of an early application of vinegar in place of an early handweeding will save 42 to 57 hours of handweeding per hectare of pepper. At a labor cost of $7/hour, this would reduce handweeding costs by 300 to 400 $/ha. The cost of vinegar direct from the supplier was 66 cents/liter, so an application of vinegar would cost less than 145 $/ha. Provided that crop injury can be reduced, there may be a cost incentive and a weed control benefit to using vinegar.

Field Trial in Brussel Sprout

Applications were made to brussel sprouts 'Oliver' at either 28 or 34 days after transplanting. Injury was greatest in the early vinegar application (43%, 2 DAT). An uneven soil surface and a small margin between the height of the sprayer nozzles and the height of the plants contributed to increased spray contact on the brussel sprouts. By the late application, the height differential between the sprayer nozzles and the plant apices had increased, and only the lowest leaves were injured (10%, 2 DAT). Thirteen days after the early application, injury was still visible (32%), whereas signs of injury had all but disappeared with the later application (1%).

Yields in both vinegar treatments were not significantly different from the handweeded treatment (Table A.3). The harvestable number of plants decreased with the early application, as some plants were stunted below a harvestable size. With the late application, harvestable number, per-plot and per-plant yields were equivalent to the handweeded treatment. Lower field weed pressure and crop vigor prevented significant yield differences between

treatments with weeds left in-row and the vinegar or handweeded treatments. Vinegar use in brussel sprouts has potential, provided the applications minimize crop contact.

Application of vinegar to brussel sprouts when weeds were at the 2-leaf stage reduced the number of in-row weeds 2 DAT (days after treatment) by 88%, compared to the weedy in-row treatment. Vinegar applications when weeds were at 4-leaves reduced the number of in-row weeds by 77% (2 DAT). Weed escapes were generally those plants that had reached a height greater

Table A.3. The mean marketable yield of brussel sprout 'Oliver'[a].

Treatment	Brussel Sprouts		
	Plants/ Plot (#)	Yield/ Plot (KG)	Yield/ Plant (KG)
Weedy Check	19 ab	15 a	0.78 a
Weedy In-Row Cultivation Between-Row, 2-lf	19 ab	13 a	0.68 a
Weedy In-Row Cultivation Between-Row, 4-lf	19 ab	14 a	0.79 a
Handweeded In-Row, 2-lf Cultivation Between-Row, 2-lf	18 b	15 a	0.80 a
Handweeded In-Row, 4-lf Cultivation Between-Row, 4-lf	20 a	16 a	0.81 a
200-Grain Vinegar In-Row, 2-lf Cultivation Between-Row, 2-lf	16 c	14 a	0.88 a
200-Grain Vinegar In-Row, 4-lf Cultivation Between-Row, 4-lf	19 ab	17 a	0.86 a

[a] Within columns, means of harvest data followed by the same letter were not significantly different ($P \leq 0.10$, Fisher's Protected LSD).

than the spray tips, and thereby avoided full contact with the vinegar. By 15 DAT, the number of weeds in the early vinegar treatment was 66% less than the weedy check, and 25% less than the number of weeds which had reemerged in the handweeded treatment.   Similarly, the number of weeds in the late treatment (15 DAT) was 64% less than the weeded check, and 19% less than that of the handweeded treatment.

Vinegar has demonstrated the potential to reduce weed pressure and may suppress weeds for longer than handweeding or cultivation. However, crop injury remains an issue. Directed applications around more mature plants, particularly tough-stemmed plants like brussel sprouts, may reduce crop injury to tolerable levels. The use of spray shielding or physical protection of plant stems may also limit crop injury.