ABSTRACT

A COMPARISON BETWEEN AUTOMATED THINNERS WITH MANUAL THINNING OF LETTUCE IN THE SALINAS VALLEY: WEED CONTROL AND EFFICACY

Automated lettuce thinners are meant to address the problems of recent labor shortages in California agriculture. Field studies were conducted in 2014 and 2015 in the Salinas Valley to compare automated thinning with manual thinning. Data were collected on crop stands, doubles (2 closely spaced plants), and weed density by species in the crop row, prior to thinning and post-thinning. Time taken for the initial thinning and the double/weed removal process, crop yield, and disease incidence was also recorded. Data were analyzed at a 0.05 level of significance. The average lettuce thinning time was 3 to 4 times quicker with the automated system than with the manual system. However, the automated system left more doubles than the manual system, thus resulting in about 90 minutes/acre more for removal of the doubles than in the manual-thinning system. Spacing of plants within rows and number of weeds removed in the crop row was similar between the 2 systems. Total and marketable lettuce yield, and *Sclerotinia minor* incidences were similar between the 2 systems. Therefore, the efficacy and efficiency of automated thinners was very similar to manual-thinning and the technology holds great potential to aid lettuce growers.

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May 2016
A COMPARISON BETWEEN AUTOMATED THINNERS WITH MANUAL THINNING OF LETTUCE IN THE SALINAS VALLEY: WEED CONTROL AND EFFICACY

by

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APPROVED

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INTRODUCTION

Lettuce (*Lactuca sativa* L.) is one of the most important leafy vegetable crops globally in terms of production (Rubatzky and Yamaguchi, 2012). Belonging to the Asteraceae family, lettuce is a self-pollinated, annual crop consisting of several types ranging from crisp, firm heads to soft, and loose leaves (Rubatzky and Yamaguchi, 2012). California is among the biggest producer of lettuce in the United States and one particular region in the state, Salinas Valley, dominates the lettuce industry in overall production (Blake, 2010a). Lettuce is generally direct-seeded in the Salinas Valley and 2 significant management practices in this production system includes thinning and weeding (Smith et al., 2011). Thinning is generally physically done by hand thinning crews while weeds are primarily controlled with herbicides (Fennimore et al., 2014). However, there are very few herbicides registered for use in lettuce production in California and not all weed species are controlled by them (Bell et al. 2000). This leads to the need for extensive hand weeding (Fennimore et al., 2014). Unfortunately, in recent years, California’s agriculture industry has been hindered by a shortage of farm labor (Taylor et al., 2012; CNBC, 2012). Thus, growers have been trying to compensate for these shortages by seeking methods to reduce the need for labor in harvesting, irrigating, thinning, or weeding (Fennimore et al., 2014). One such method is the use of modern technology in the form of automated lettuce thinners. These automated lettuce thinners are being tested in the Salinas Valley and are meant to replace the traditional thinning practices with hand hoes (hereafter referred to as manual thinning) and cleaning crews. The machine also ensures adequate spacing of lettuce plants in a row for optimal growth and high yield and controls weeds concurrently (R. Smith, personal communications). Growers are
now at the point of considering or evaluating these machines in their own fields. However, it is necessary to compare these automated thinners with manual thinning in direct-seeded lettuce, specifically their efficacy and weed control in California’s Salinas Valley. Such information would help lettuce growers in their decision to adopt this new technology.
LITERATURE REVIEW

Global/United States Lettuce Industry

Lettuce is considered to be the most important leafy vegetable crop globally in terms of production. According to Rubatzky and Yamaguchi (2012), *Lactuca sativa* is the only domesticated species in the *Lactuca* family and it is a native of the eastern Mediterranean basin. The authors further state that ancient cave paintings in Egypt indicate the use of wild lettuce as early as 4500 B.C., which many believe was for medicinal purposes during this time period. Today, there are reportedly more than 100 wild species in the *Lactuca* family, with Asia and Africa having the highest species variation, 51 and 43 species, respectively (Lebeda et al. 2004). These wild relatives usually contain bitter spiked leaves and stems as well as an abundance of latex. They also elongate and form seed, or bolt, quickly, and do not form heads as domesticated lettuce. Throughout the years, the plants that form heads, have large, crisp tasting broad leaves, and are much slower at bolting have been preferred and selected in the breeding process. In 1543, the first indication of heading lettuce was reported as cabbage lettuce (Rubatzky and Yamaguchi, 2012).

Today, consumption of this crop is mostly in the form of a fresh vegetable, such as in salads, but it may be cooked as well (Rubatzky and Yamaguchi, 1997; Lebeda et al. 2007). Leading lettuce producing countries in the world include China, the U.S., Spain, India, and Italy (Figure 1). Lettuce is the most commonly used vegetable in salads, and in some countries it is consumed in high enough amounts that it makes a positive nutritional contribution (Rubatzky and Yamaguchi, 2012). World lettuce production is now estimated to be over 3 million tons and the crop is grown in more than 300,000 hectares (Figure 2).
Figure 1. Major lettuce producing countries of the world (average of 2003 to 2005). Source: AGMRC (2012).

Figure 2. Average annual area (in acres) under lettuce production from 1980 to 2004. Source: Rubatzky and Yamaguchi (2012).
Commonly found in the western diet, it is believed that domesticated lettuce has been grown in the U.S. since colonial times and was brought to the new world by explorer Christopher Columbus (Boriss and Brunke, 2005; Economic Research Service, 2011). Lettuce is now the leading vegetable crop in terms of production and has the second highest consumption rate for fresh vegetables at 12.7 kilograms (28.0 pounds) per capita, only behind potato (*Solanum tuberosum* L.) which has a consumption rate of 16.7 kilograms (36.7 pounds) per capita in the U.S. (Boriss and Brunke, 2005; Economic Research Service, 2011). Lettuce is grown year round in the U.S., with California primarily supplying market demand from April to October, and Arizona primarily supplying from November to March (Boriss and Brunke, 2005).

According to Borris and Brunke (2005), there are only a few companies which grow, process, and distribute lettuce to the U.S. market. The current lettuce market has been dominated by bagged lettuce products, as the market saw an increase in sales of these products from 1993 to 1999 from $197 million to $1.3 billion. This in part was also due to advancements in technology in the form of better packing material, which allowed for more varieties to be available throughout the year. The driving force of the lettuce industry has been freshness, easy access to this commodity, and availability of different varieties throughout the year. This is supported by the fact that iceberg, or crisp, lettuce consumption peaked in demand in 1989, and has exhibited a steady decrease in overall consumption since romaine and other leaf lettuce varieties became more readily available (Figure 3). This trend is believed to have arisen because of the market’s preference for romaine in bagged products and leaf lettuce’s popularity in salad bars. The U.S. is also the second largest exporter of lettuce, with about 20 percent of total production going to countries such as Canada, Mexico, and Japan. Japan
is the largest exporter lettuce into the U.S. Less than 5 percent of this imported lettuce from Japan into the U.S. represents the yearly total (Boriss and Brunke, 2005).


**Lettuce Biology and Physiology**

Lettuce belongs to the Asteraceae family and is a self-pollinated, annual, polymorphic plant (Nagata et al. 2007; Rubatzky and Yamaguchi, 2012). Early in its growth stage, lettuce begins to develop a large, thick tap root accompanied by many thick lateral roots from which most of the nutrients and moisture are taken up (Rubatzky and Yamaguchi, 2012). The species of lettuce most common in the market in recent years are mostly genetic improvements from *L. serriola*, *L.*
saligna, and L. virosa, which can usually be readily found along roadsides and ditches (Lebeda et al., 2001; Lebeda et al., 2004; Lebeda and Petrzelova, 2004; Lebeda et al., 2007). Lettuce plants are variable in the morphology of its fleshy leaves and varieties range from crisp, firm heads to soft, loose leaves (Nagata et al. 2007). Today, the crop consists of 7 main types of cultivars which differ phenotypically. They include Butterhead lettuce, Kripshead lettuce, Cos lettuce, Cutting lettuce, Stalk (Asparagus, stem) lettuce, Latin lettuce, and Oilseed lettuce (Křístková et. al., 2008) (Figure 4). Most varieties have a cylindrical stem which is short and stout. One exception is Stalk lettuce, which is harvested not for its leaves, but for its stem (Rubatzky and Yamaguchi, 2012). With a basal rosette of leaves up to 15 cm (10 in) in length, lettuce leaves grow slightly or firmly bunched, and are generally harvested before the flowering stem has bolted. If allowed to bolt, the plant may elongate and branch, reaching nearly 1 m (3 ft) in height, with yellow composite flowers (Rubatzky and Yamaguchi, 2012; Corteau, 2015). The inflorescence contains a dense corymbose panicle of many capitula, each of which contain anywhere from 10 to 25 florets which are usually self-pollinated, but cross-pollination can also occur (Rubatzky and Yamaguchi, 2012). Flowering occurs for 1 to 2 months, however, seed formation is kept unanimous within the florets, as every floret only opens for a short period each morning. One seed, no bigger than a few millimeters, forms within each floret, and are prone to shattering, or breaking open (Rubatzky and Yamaguchi, 2012).

Lettuce, like the majority of terrestrial plants, uses C₃ photosynthetic metabolism pathway to convert light into energy. This process is accomplished by the intake of CO₂ by the plant leaves, which then binds with Ribulose, otherwise known as Rubisco (1,5-biophosphate carboxylase/oxygenase) in the plant cell’s
chloroplasts (Boulard, 2008). This process then begins the production of phosphoglyceric acid, a 3-carbon sugar which is the driving force for most chemical reactions within a plant (Boulard, 2008).

Lettuce can be grown in a wide range of soil types such as sand soils, which drain easily, to clay soils, which hold water more readily (Zandstra et al, 1983; Wien, 1997). However, when growing lettuce, planting date should be taken into consideration along with soil type. For example, planting in a loam to clay soil during warmer months of the year would prevent evaporative losses, while planting in a sand to sandy-loam soil during cooler months of the year would prevent soil borne diseases such as root and bottom rot that arise from extended periods of water logging (Zandstra et al, 1983; Nonnecke, 1989; Wien, 1997).

Soils used for lettuce production should be high in organic matter, have adequate nutrient levels within the upper 25-30 centimeters (9.8-11.8 inches), and a pH of 6.0-6.5 or 7.5-8.0 depending on soil type (Nonnecke, 1989). If soil pH is less than 6.0, then the soil should be amended before seeding (Nonnecke, 1989). It is essential to rotate lettuce with a crop which is not affected by the same soil borne diseases such as tomatoes, cucurbits, carrots, beets, or sweet corn. (Zandstra et al, 1983; Nonnecke, 1989).

Being a cool season crop, lettuce seeds germinate at a minimum soil temperature of 35°F (1.7°C) and a maximum of 84.9°F (29.4°C) (Wien, 1997). Optimal temperature conditions for lettuce growth are a day time temperature of 73°F (23°C) and night time temperature of 45°F (7°C) (Smith et el., 2011). For example, under these conditions, romaine matures within 60 to 65 days after seeding, iceberg matures within 63 to 68 days, leaf lettuce matures within 50 to 55 days, and butter leaf lettuce matures within 55 to 60 days during summer (Cahn, 2014).
Nearly all lettuce cultivars have been bred to inhibit bolting, however, if the aim of a planting is for seed production, then a combination of photoperiod, temperature effects, and vernalization practices should be implemented (Wien, 1997). For instance, flowering is accelerated under 16 compared to 9 hour photoperiods, however, this may vary depending on cultivar (Rappaport and Wittwer, 1956a). If average daytime temperatures should rapidly rise over 64° F (18° C) and if nighttime temperatures are at 70° F (21° C) for an extended number of days, this can initiate the plant to bolt and flower much sooner than at the optimal growing temperatures described above (Nonnecke, 1989; Wien, 1997). If low temperatures of 39° F (4° C) arise 1-3 days prior to seeding for 5-20 days, bolting may occur 3 to 5 days sooner at optimal growing conditions (Knott et al., 1939; Rappaport and Wittwer, 1956b; Prince, 1980).

Various physiological disorders may arise in lettuce if unfavorable conditions are present. For example, tip burn can occur because of uneven distribution of calcium in irrigation water, which blemishes the plant by causing edges of leaves to become chlorotic and necrotic, and eventually rot (Zandstra et al, 1983). Brown rib is also a physiological disorder in which the outer leaf cells start turning brown. This eventually spreads throughout all leaves and gives the plant a defined striped look which is undesirable for market. Ribbedness is a physiological disorder in which the lettuce plant early on in its development develops uneven, loose, leaves with large midribs which inhibits the formation of a head (Zandstra et al, 1983).

**Lettuce Diseases**

Various fungal, bacterial, and viral diseases currently effect lettuce production. According to Koike et al. (2006a), the most widespread and prominent
lettuce diseases worldwide are caused by fungus. Lettuce drop is considered the most important soil-borne disease in California and other similar climatic regions, with as much as 75% of an area being affected by this soil-borne pathogen. This disease is caused by 2 fungus species, *Sclerotinia minor* and *S. sclerotiorum*. Both produce similar visual symptoms on a plant, once infection takes place. These include browning and decaying of older leaves and stem in contact with the soil, and complete collapse of the plant once it nears harvest. Small, black, irregularly shaped sclerotia form on the base of the plant as well, which act as the disease’s overwintering vessel, which are surrounded by white powdery mycelium. The difference between *S. minor* and *S. sclerotiorum* is that the latter forms sclerotia which are slightly larger than that of the former (3-5 mm vs. 5-10 mm), from which apothecia emerge. Spores are also produced from *S. sclerotiorum*, which allows for infection of plant tissue above the soil through wind dispersion. Control of these fungi can be accomplished by a combination of fungicide use after the field has been thinned, crop rotation, and plowing of soil to bury sclerotia (Koike et al., 2006a). There has also been some speculation among growers as to whether or not this disease spreads more readily when young plant roots are exposed after manual thinning; however, no studies have been conducted to verify this (R. Smith, personal communications).

Downy mildew (*Bremia lactucae*), is reportedly the most significant foliar disease of lettuce, as it has the potential to contaminate all lettuce types and cause high yield losses (Cobelli et al. 1998). Disease symptoms include light green to yellow blotches on older leaves, which later turn dry and brown with the appearance of a white, powdery substance on the underside of the leaf. High yield loss occurs when large amounts of leaves are removed in order to eliminate the blemished part of the plant (Cobelli et al., 1998). This disease mostly occurs
during humid, cool climatic conditions which initiate spore rupture, and control is best accomplished with a combination of use of resistant varieties and application of fungicides prior to planting (Davies, 1994; Scherni and van Bruggen, 1994).

Fusarium wilt (*Fusarium oxysporum* f. sp. *lactucae*) is one of the newest fungal diseases introduced into California during the early 1990’s. This disease now presents a great challenge for lettuce growers throughout the Southwestern U.S. (Matheron and Koike, 2003). Symptoms usually occur on seedlings, which causes loss of growth, wilt, and usually death. The internal part of the infected root becomes discolored, usually having a red to brown hue opposed to an opaque white color, with a red to brown color developing around the cortex of the crown of the plant as well (Fujinaga et al., 2001). Symptoms may also arise on older plants, with the same root symptoms occurring and tissue becoming necrotic and wilted (Hubbard and Gerik, 1993). The only control known for this disease is planting varieties which are less susceptible to infection, such as romaine lettuce, or planting only during the early spring when disease occurrence is minimized. It is also important to try and prevent the spread of contaminated soil into clean soil (Matheron and Koike, 2003).

Various other fungal, viral, and bacterial diseases impact lettuce production. These include gray mold (*Botrytis cinerea*), powdery mildew (*Golovinomyces cichoracearum*), phoma basal rot (*Phoma exigua*), bottom rot (*Rhizoctonia solani*), lettuce mosaic virus, lettuce dieback virus, tomato spotted wilt virus, aster yellows (*Aster yellows phytoplasma*), varnish spot (*Pseudomonas cichorii*), corky root (*Rhizomonas suberifaciens*), and bacterial leaf spot (*Xanthomonas campestris* pv. *vitiens*) (Grogan et al., 1977; Crute and Burns, 1983; Wareing et al., 1986; Cho et al., 1987; van Bruggen et al., 1990; Lee et al., 1992;
Nutritive Value of Lettuce

Consumer’s today push markets for products which are nutritious, compliment a healthy lifestyle, prevent illness, and aid in supporting long lifespans (Mou, 2011). According to Ryder (2003), lettuce contains many of the same nutrients as other green vegetables, only in smaller amounts (Ryder, 2003). These nutrients consist of minerals, vitamins, and fiber (Ryder, 2003). Within the various types of lettuce, romaine and leaf varieties surpass crisphead and butterhead varieties for most of the common nutrients (Ryder, 2003). This is directly related to the proportion of dark green leaves in the edible portion (Ryder, 2003). For example, crisp lettuce contains 22 g of calcium, 26 g of phosphorous, and 7 g of potassium per 100 g of lettuce, whereas romaine lettuce contains 44, 35, and 9 g, of these minerals, respectively (Ryder, 2003).

Along with nutritive value, consumers also push for quality products which are reflective of taste, texture, size, shape, color, and are free from blemishes and diseases (Kader et al., 1973; Arthey, 1975; Ryder, 1999; Simonne et al., 2002). Leaf color is considered one of the most important quality indicators when it comes to lettuce because it is one of the first traits which indicates whether or not a consumer will purchase that product (Ryder, 1999b). This coloration may be based, in part, on anthocyanin and chlorophyll levels (Gazula et al., 2005), which contribute to leaf color and, ultimately, product appeal (Gazula et al., 2007). Anthocyanin and chlorophyll concentrations in numerous tissues of horticultural crops, including lettuce, are influenced by biotic (genetics, growth stage, disease) and abiotic (temperature, light, water potential, nutrient availability) factors (Maza
and Maniati, 1993; Shvarts et al., 1997a, 1997b; Oren-Shamir and Levi-Nassim, 1999; Reay, 1999; Wang and Zheng. 2001; Shaked-Sachray et al., 2002; Dela et al., 2003). In lettuce, a corresponding gene pair (CcGg) influences the presence or absence of anthocyanins, predominantly cyanidin 3-malo-nylglucoside (Yamaguchi et al., 1996), while a multiple allelic system runs the form of red colorations (Thompson, 1938; Robinson et al., 1986; Ryder, 1999).

**Agronomic Practices for Lettuce Production**

In recent years, most lettuce in California is planted using coated seeds with a precision planter (Turini et al., 2011), with little being transplanted, if only to speed up the growth process when demand is very high (Smith et al., 2011). Approximately 90% of lettuce is direct-seeded and 10% is transplanted (Turini et al., 2011). Seeds are generally planted very shallow, about 0.318 cm (1/8 of an in.) deep, and 5 - 7.5 cm (2 to 3 inches) apart, on raised, flat beds 102 cm (40 in) wide with 2 rows, or 203 cm (80 in) with 5-6 rows (Smith et al., 2011; Turini et al., 2011; Cahn, 2014). With preferences kept in mind, the amount of seeds planted within an area can range from 258,375 to 581,820 seeds per/ha (104,550 to 235,460 seeds/acre) (Smith et al., 2011; Turini et al., 2011). After the seedlings emerge, the plants are thinned approximately at the 2 to 3 leaf stage (Figure 5) (Blake, 2010b). This thinning process is accomplished by crews physically spacing plants by removing some with hand hoes (Figure 6). Plants are spaced 25.4 to 30.48 cm (10 to 12 inches) apart (Smith et al., 2011) and weeds which have emerged are removed at the same time (Fennimore et al., 2014). Studies have found that the time taken to thin a lettuce field is positively correlated with the number of weeds present in that field (Haar and Fennimore, 2003). Another pass with a crew occurs 2 to 3 weeks after the initial thinning to remove weeds.
which may have emerged and the doubles (2 closely spaced plants which occurred because of seeding error) (Figure 7). Doubles are usually missed during the first pass because of the small size of the plants which makes it difficult to define one plant from 2 (Figure 8) (Turini et al., 2011).

Figure 5. A crew physically thinning lettuce with long handled hoes. Picture source: www.yumasun.com

Figure 6. A bed of lettuce half-way thinned by a manual-thinning crew.
Figure 7. A crew physically removing doubles and weeds 2 weeks after thinning.

Figure 8. A picture showing what is considered as a “double” in lettuce production.
All lettuce varieties transpire at high rates, making a constant source of water necessary from seeding to harvest in order to avoid irreversible damage to the crop (Nonnecke, 1989). According to Cahn (2014), the main factors which should be taken into consideration while scheduling irrigation for lettuce are soil texture, temperature throughout the crop cycle, amounts of salinity in irrigation water and soils, and irrigation practices. The best soils for growing lettuce are loam to clay loam soils, as they contain a good combination of water holding and drainage capacities for lettuce (Zandstra et al., 1983; Nonnecke, 1989; Wien, 1997). According to Cahn (2014), there are 3 main forms of irrigation practiced in California. The first is furrow irrigation, which has not been implemented as much as in past years because of drought conditions paired with its non-uniform distribution of moisture throughout the field. Second is sprinkler irrigation, which is commonly used during the first half of the growth stage of lettuce because of even distribution of high amounts of water, unless compromised by winds greater than 5 miles per hour. And last, drip irrigation, which is very commonly used in the second half of the growth stage of lettuce because of the ability and ease to distribute high amounts of water and fertilizer frequently in very localized sections of the field, usually very close to the plant root, during the growth stage where lettuce needs highest applications of water and fertilizer. At the time of bed preparation and after seeding, irrigation is recommended every 2 to 3 days with 2 to 4 inches (5-10 cms) of water applied with sprinklers until seeds have germinated, approximately 6-10 days after planting (Cahn, 2014). After germination, the field is irrigated less frequently. Surface drip is usually installed after the field has been thinned with irrigation occurring approximately every 7 days. As the crop’s canopy and root size increases, irrigation intervals should increase. The final 2 weeks of growth are the most critical for irrigation, as most
varieties of lettuce need highest volumes of water and length of irrigation during this time (Cahn, 2014).

According to Hartz (2014), for fertilizing lettuce, the required amount of fertilizer should predominantly be determined through pre-plant soil sampling to fulfill individual field’s nutritional needs. Soil samples collected for nutrient analysis should be a representative example of the entire field. After the analysis, interpretation of the results may be accomplished using a standard soil analysis and interpretation chart.

Nutrient application will always vary between individual fields; however, most fields used to grow lettuce in California are sufficient in potassium (K) and micronutrients but they lack phosphorous (P), and need incorporation of nitrogen (N) at key growth stages (California Department of Food and Agriculture, 2011). If K is low or moderate in a field, both of which are usually rare occurrences, K is commonly applied as a pre-plant fertilizer, or before seeding has occurred. P is usually applied as a pre-plant fertilizer or at time of planting unless the field does not need so much P, in which case it is just applied as a starter fertilizer. N is considered the most essential nutrient when growing lettuce, as moderate amounts are usually necessary at pre-plant, sowing, and rosette stages, and large amounts being necessary from head development to harvest (California Department of Food and Agriculture, 2011).

Lettuce Industry in the Salinas Valley of California

California’s lettuce industry is an imperative facet of its fresh produce market. With nearly 80937 hectares (200,000 acres) of land dedicated for the production of head, leaf, and romaine lettuce, a total crop value of over $2 billion was produced in the 2014 cropping year (USDA and NASS, 2014). California’s
major lettuce production areas include the southern coast (Santa Barbara and Ventura Counties), the Central Valley (Fresno, Kings, and Kern Counties), and the Central Coast (Figure 9) (Monterey, San Benito, Santa Cruz, Santa Clara, and San Luis Obispo Counties) (Smith et al., 2011). Of these regions, one area dominates the lettuce industry in overall production, Monterey County, Salinas Valley. Properly nicknamed “The Salad Bowl of the World” (Souza, 2009), Monterey County alone produces over 57% of lettuce grown in California (USDA and NASS, 2014). This fact is impressive, important, and significant, because Monterey County, only having an area of 8,604 km$^2$ (3,322 sq. mi.) produces nearly half of the nation’s lettuce (Geisseler and Horwath, 2014).

Figure 9. Map of California highlighting all major lettuce producing counties ranging from <10% to >30% of the total U.S. production. Picture Source: Park and Lurie (2014).
According to Griffin and White (1955), Salinas Valley’s lettuce industry arose because of several key events in the area’s cropping history. In the 1920’s, the Salinas Valley’s staple crop, sugar beet (*Beta vulgaris* L.), was beginning to return poor yields. Meanwhile, the Los Angeles area, leading in lettuce production at the time, was experiencing vivid suburban growth, which resulted in encroachment on land previously used for lettuce production. This growth soon led to Los Angeles becoming unable to meet the lettuce market demand. Without a staple crop, these events led growers in the Salinas Valley to begin lettuce production. The transition from sugar beets to lettuce did not pose many problems for growers in the area. Sugar beet and lettuce are both labor-intensive crops, thus the labor force which maintained sugar beet began to manage lettuce quite efficiently. Transportation of the crop was easily maintained as well, for rail road tracks which had been placed along the middle of the valley for sugar beet transportation began to transport lettuce, and the packing. Most areas around Monterey County have daytime temperatures from 63-83° F (17-20° C), and nighttime temperatures from 37-53° F (3-12° C). Due to these climatic conditions, the Salinas Valley has one of the longest growing seasons in the nation for lettuce. The climate allows planting from late-December to mid-August and harvesting from early-April to November (Smith et al., 2011). These environmental conditions paired with the Salinas Valley’s clay loam to sandy loam soils make ideal conditions for growing high quality lettuce (Griffin and White, 1955; Petrick, 2006). These aspects led to the domination of the lettuce crop and industry in the area and market.
Weed Management in Lettuce

Grower investment is significant in every aspect of the lettuce growing process, including thinning and weeding. Weeds are one of the most common pests when it comes to vegetable crops (Figure 10) (Fennimore et al. 2014). Representing a total yield loss of 12% in the United States, $33 billion are lost yearly because of weed infestations in lettuce (Pimentel et al., 2001). Weeds compete with crops for essential nutrients and water in the soil, hold the potential to transmit diseases, delay harvests, and if present in harvested produce, contaminate the crop (Bell 1995; Haar and Fennimore, 2003). If a lettuce field is infested with 25% weed coverage, the result is a loss of up to 40% yield, and anything greater than 25% weed coverage results in a complete loss of yield (Lanini and LeStrange, 1991). It is imperative that growers have a set integrated pest management (IPM) program for managing weeds because of the market’s low tolerance for blemished or visibly unappealing vegetable crops (Fennimore et al., 2014).

Lettuce plants are short and have a slow growing canopy during early development, which makes it difficult for these young plants to compete with weeds (Odero and Write, 2013). The critical period of weed control (CPWC) is the contingency of both the critical timing of weed removal (CTWM), or the maximum amount of weeds a crop can compete with until yield becomes compromised, and the critical weed free period (CWFP), or the minimal amount of time a crop can be weed-free from the time of planting in which yields will not be negatively impacted (Knezevic et al., 2002; Zimdahl, 2011). The CTWM and CWFP are meant to indicate when CPWC should begin and end (Norworthly and Oliveira, 2004). The CTWR for lettuce is reported to range from 13 to 29 days but
this seems to be influenced by the type of weed species present (Fennimore and Umeta, 2003; Santos et al. 2004a, 2004b; Kaymak, 2007).

Figure 10. Weeds within a crop row in lettuce.

Weeds are managed primarily with herbicides and hand hoeing in California’s lettuce industry (Fennimore et al., 2014). Herbicide use is challenging and expensive because there are very few registered chemicals for use in California and none of them control all weed species common in lettuce fields (Bell et. al. 2000). When herbicide use is ineffective, it results in more extensive hand weeding. One example is with the herbicide Kerb (pronamide), which is best at controlling broadleaf weeds in lettuce, predominantly shepherd’s purse (Capsella bursa-pastoris), arguably the most problematic weed in lettuce (Blake, 2010a), but it is ineffective against several other species.
The average cost of iceberg, romaine, and organic leaf lettuce production is $19,766, $21,861, and $24,493/ha, ($7,999, $8,847, and $9,912/ac), respectively (Blake, 2010b). Of these costs, approximately 11% accounts for weed management (Tourte and Smith 2001; PMSP-Lettuce 2003). Costs for thinning and hand weeding have been reported to range from $247/ha ($100/ac) to $444/ha ($179/ac) (Tourte and Smith, 2009; Blake, 2010a).

**Labor Shortage Effects on Lettuce Industry**

In recent years, California’s agriculture industry has been hindered by a shortage in labor. According to statistics from The National Agricultural Workers Survey, 75% of the crop workers in the U.S. were originally from Mexico and immigrated into the U.S. (United States Department of Labor, 2010). These migrant workers have been immigrating into the U.S. in smaller numbers in recent years. Starting in the 2008 recession, migration from Mexico to U.S. began to decrease dramatically (Taylor et al., 2012). Therefore, in recent years, there is a significant lack of laborers to help growers perform the necessary tasks to make their products go from field to market in a timely manner. In an attempt to keep up with the market demand, some growers have resorted to working longer hours throughout the work week. Meanwhile, others have to pay more for labor all while attempting to entice new workers to enter their own work force. (CNBC, 2012). It is imperative for researchers and growers alike to continuously invest in one of California’s highest grossing commodity crops by finding new, innovative ways to protect grower investments.

**Automated Lettuce Thinners**

In recent years, growers have been trying to compensate for these labor shortages in various ways. Some of the most promising of these ideas are
technological interventions, otherwise known as precision agriculture (Zhang et al., 2012), which performs some aspect of the field operations that are usually performed manually, whether it be harvesting, irrigating, thinning, or weeding (Fennimore et al., 2010). The use of mechanical implements for thinning and weeding, which are important for the Salinas Valley, date back to when sugar beet was the staple crop of the valley (Mervine and Barmington, 1943). In recent years, developments are focused on site-specific weed management where herbicide application is aimed at targeting weeds at a much more concentrated level (Christensen et al., 2009). Some crops in which these technologies have been implemented in are sugar beet, cotton, and transplanted cabbage (Lamm et al., 2002; Astrand and Baerveldt 2002, 2004 and 2005; Tillett et al., 2008).

One such form of technology being tested in the Salinas Valley in recent years is automated lettuce thinners. In 2012, when labor shortage was detrimental in the Salinas Valley, the arrival of automated lettuce thinners sparked interest in growers (R. Smith, personal communications). The objectives of the use of these automated lettuce thinners were to replace the traditional manual-thinning and cleaning crew that ensured adequate spacing of the lettuce plants for optimal growth and high yield. These automated thinners use ‘machine vision’ technology in the form of an infra-red camera which allows it to define a plant and helps it choose the plants to keep and the ones to eliminate using chemicals such as glyphosate, pelargonic acid, paraquat dichloridegramaxone and carfentrazone, and salt- based and acid-based fertilizers such as AN20, UN32, ammonium thiosulfate, NpHuric, and other materials such as sulfuric acid (Figure 11). As of 2016, the companies offering automated lettuce thinning technology to growers in the Salinas Valley include Foothill Packing, Gonzales, CA; Blue River Technology, Mountain View, CA; and Vison Robotics, San Diego, CA (Figures 12, 13, and 14).
(Smith, 2014). However, the principles and mechanical functions of the machines from these various manufacturers are generally identical. Lettuce growers in the Salinas Valley are now at the point of considering or evaluating these machines for their own use.

Figure 11. Lettuce beds thinned by an automated lettuce thinner.

Figure 12. Foothill Packing Automated Thinner.
Figure 13. Ag Metronix Automated Thinner. Photo source: Smith, R. (2016)

Figure 14. Blue River Technology Automated Thinner. Photo source: Smith, R. (2016)
Perceived Problems with Automated Lettuce Thinners

There are various aspects which must be determined regarding these automated lettuce thinners before their widespread adoption. These predominantly include how they compare to the process of manual-thinning in efficiency and efficacy. Because these mechanical implements rely on camera technology which identifies a certain color, in this case green because of the lettuce plant, it needs to be determined how well it is able to distinguish a lettuce plant from a weed or other volunteer plants (Figure 15). Similarly, it also needs to be determined how it responds to the presence of doubles, i.e. 2 lettuce plants at close proximity, because of planting error. It is also assumed that the infra-red camera may mistake weeds for lettuce plants, therefore reducing stand counts, or fail to spray the weeds which are in close proximity to the lettuce plants. It is also interesting to verify if the automated thinners will leave behind smaller lettuce plants compared to manual-thinning. Manual-thinning crews usually select a larger lettuce plant to keep and thin out the smaller one, if the opportunity is present (Figure 16). Other important aspects of the thinning and weeding process of lettuce include information on spacing between plants, weed densities, stand counts, number of doubles, time taken for thinning and weeding, and its effect on disease transmission. Therefore, studies should be conducted to evaluate these parameters for successful incorporation and widespread adoption of automated lettuce thinners in the lettuce cropping system of the Salinas Valley. Such studies will provide growers practical and pragmatic answers as to whether these implements will mesh with their cropping practice preferences.
Figure 15. Weed in the place of a lettuce plant after thinning.

Figure 16. Size difference in lettuce after thinning.
OBJECTIVE

The objective of this study was to compare the efficiency and efficacy of automated thinners with manual-thinning of lettuce in California’s Salinas Valley.
MATERIALS AND METHODS

Project Site Set Up

Field experiments were conducted in 2014 and 2015 in various locations in the Salinas Valley of California. Experimental plots were provided by lettuce growers who were currently using or evaluating automated thinners for their own use. In 2014, 7 sites were used for the experiment. These sites ranged from Gonzales to Salinas, California (Table 1). Prior to the initiation of the experiments, the number of beds at each site were counted. This was done to verify the midpoint of the field, which was selected to act as the divider between treatments. After each field sites’ midpoint were located, each half of the field was randomly assigned a treatment of either thinning with the automated thinners or manual-thinning by hand hoes. Size of lettuce beds were all 1.01 m (40 in) with 2 seedlines, with the exception of one with 2.02 m (80 in) beds and 5 seedlines (Table 1). Within each plot, 4 to 10 sub-plots were randomly chosen within the treatment areas. However, edges of the field were avoided. These sub-plots were on one bed that was 1.01 m (40 in) wide and 9.1 m (30 ft) long. For the experimental site with 2.02 m (80 in) beds and 5 seedlines, each sub plot measured 4.6 m (15 ft). Each end of the sub-plots were marked with flags. Planting dates ranged from May 2 to June 2, 2014, with seeding being accomplished with a precision seeder planting at a maximum depth of 0.318 cm (1/8 of an in.), and 5 - 7.5 cm (2 to 3 inches) apart, and harvest dates ranged from July 1 to August 12, 2014 (Table 2) depending on the site. In 2015, the experiment was conducted only at one site in Soledad, California (Table 1). Similar to 2014, the number of beds were also counted and then evenly divided into 4 blocks. Each block was further subdivided into 2 plots and each plot contained 4 beds that were randomly
assigned a treatment of either automated thinning or manual-thinning. The sub-plots consisted of 2.02 m (80 in) beds with 6 seedlines, the sub-plots were 3.048 m (10 feet) long (Table 2). Each end of the sub-plots were marked with flags. Seeding occurred on May 30, 2015 with a precision seeder planting at a maximum depth of 0.318 cm (1/8 of an inch), and 7.5 cm (3 in) apart. Harvest occurred from July 27 to 29, 2015 (Table 2).

Table 1. List of trial sites.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Year</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2014</td>
<td>Gonzales, CA</td>
</tr>
<tr>
<td>2</td>
<td>2014</td>
<td>Salinas, CA</td>
</tr>
<tr>
<td>3</td>
<td>2014</td>
<td>Salinas, CA</td>
</tr>
<tr>
<td>4</td>
<td>2014</td>
<td>Salinas, CA</td>
</tr>
<tr>
<td>5</td>
<td>2014</td>
<td>Salinas, CA</td>
</tr>
<tr>
<td>6</td>
<td>2014</td>
<td>Salinas, CA</td>
</tr>
<tr>
<td>7</td>
<td>2014</td>
<td>Salinas, CA</td>
</tr>
<tr>
<td>1</td>
<td>2015</td>
<td>Soledad, CA</td>
</tr>
<tr>
<td>2</td>
<td>2015</td>
<td>Soledad, CA</td>
</tr>
<tr>
<td>3</td>
<td>2015</td>
<td>Soledad, CA</td>
</tr>
<tr>
<td>4</td>
<td>2015</td>
<td>Soledad, CA</td>
</tr>
</tbody>
</table>

Starting on May 8 to August 6 for the 2014 season and starting on June 14 to June 24 for the 2015 season, at each experimental site, stand counts of the lettuce plants within each sub-plot were taken to assess the number of plants within these areas prior to the thinning process. Number of weeds in each sub-plot were also counted by species and recorded. However, only those weeds within 2
Table 2. Details on the variety, type of lettuce, configuration of the beds, and planting and harvesting dates at each site.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Year</th>
<th>Variety</th>
<th>Type</th>
<th>Configuration</th>
<th>Planting Dates</th>
<th>Harvest Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2014</td>
<td>Declaration</td>
<td>Head</td>
<td>40&quot;; 2</td>
<td>2-May</td>
<td>15-17-Jul</td>
</tr>
<tr>
<td>2</td>
<td>2014</td>
<td>Champion</td>
<td>Head</td>
<td>40&quot;; 2</td>
<td>26-Apr</td>
<td>1-4-Jul</td>
</tr>
<tr>
<td>3</td>
<td>2014</td>
<td>Mondo</td>
<td>Romaine</td>
<td>40&quot;; 2</td>
<td>11-May</td>
<td>14-18-Jul</td>
</tr>
<tr>
<td>4</td>
<td>2014</td>
<td>Telluride &amp; Regency</td>
<td>Head</td>
<td>40&quot;; 2</td>
<td>27-May</td>
<td>28-Jul</td>
</tr>
<tr>
<td>5</td>
<td>2014</td>
<td>Telluride &amp; Regency</td>
<td>Head</td>
<td>40&quot;; 2</td>
<td>10-Jun</td>
<td>12-Aug</td>
</tr>
<tr>
<td>6</td>
<td>2014</td>
<td>Big Star</td>
<td>Green Leaf</td>
<td>80&quot;; 6</td>
<td>2-Jun</td>
<td>30 Jul-1 Aug</td>
</tr>
<tr>
<td>7</td>
<td>2014</td>
<td>Mondo</td>
<td>Romaine</td>
<td>40&quot;; 2</td>
<td>11-Jul</td>
<td>16-Sep</td>
</tr>
<tr>
<td>1</td>
<td>2015</td>
<td>Darkland</td>
<td>Romaine</td>
<td>80&quot;; 5</td>
<td>30-May</td>
<td>27-29 Jul</td>
</tr>
<tr>
<td>2</td>
<td>2015</td>
<td>Darkland</td>
<td>Romaine</td>
<td>80&quot;; 5</td>
<td>30-May</td>
<td>27-29 Jul</td>
</tr>
<tr>
<td>3</td>
<td>2015</td>
<td>Darkland</td>
<td>Romaine</td>
<td>80&quot;; 5</td>
<td>30-May</td>
<td>27-29 Jul</td>
</tr>
<tr>
<td>4</td>
<td>2015</td>
<td>Darkland</td>
<td>Romaine</td>
<td>80&quot;; 5</td>
<td>30-May</td>
<td>27-29 Jul</td>
</tr>
</tbody>
</table>

cm on either side and in between plants on the same seedline (crop row) were counted. This was done so because the objective was to evaluate the efficacy of the automated thinners compared to the manual-thinning process within the seedline, as the weeds in immediate proximity of the crop row that is of greatest concern to the growers. The weeds in between seedlines, edges of beds, and furrows are primarily managed with mechanical cultivation. The weeds in the
area sampled, as described above, are more difficult to remove and cause the
greatest yield losses. The number of lettuce doubles within each sub-plot was also
counted and recorded (Table 3).

Table 3. Dates when counts were taken on lettuce plants, weed, and double plants
in the treatment plots prior to thinning.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Year</th>
<th>Lettuce</th>
<th>Weeds</th>
<th>Doubles</th>
<th>Lettuce</th>
<th>Weeds</th>
<th>Doubles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2014</td>
<td>19-May</td>
<td>19-May</td>
<td>19-May</td>
<td>27-May</td>
<td>27-May</td>
<td>27-May</td>
</tr>
<tr>
<td>2</td>
<td>2014</td>
<td>8-May</td>
<td>8-May</td>
<td>8-May</td>
<td>21-May</td>
<td>21-May</td>
<td>21-May</td>
</tr>
<tr>
<td>3</td>
<td>2014</td>
<td>24-May</td>
<td>24-May</td>
<td>24-May</td>
<td>2-Jun</td>
<td>2-Jun</td>
<td>2-Jun</td>
</tr>
<tr>
<td>5</td>
<td>2014</td>
<td>24-Jun</td>
<td>24-Jun</td>
<td>24-Jun</td>
<td>5-Jul</td>
<td>5-Jul</td>
<td>5-Jul</td>
</tr>
<tr>
<td>7</td>
<td>2014</td>
<td>24-Jul</td>
<td>24-Jul</td>
<td>24-Jul</td>
<td>1-Aug</td>
<td>1-Aug</td>
<td>1-Aug</td>
</tr>
</tbody>
</table>

1Automatedly-thinned plots
2Manually-thinned plots

During the lettuce thinning process, the time taken to thin each treatment
plot was recorded with a stop watch (Table 4). For the manually-thinned plots, a
crew of approximately 15 to 25 members was present. Each crewmember was
equipped with one hand hoe with the metal attachment at the end of the hoe being
6 to 9 inches long. Traditionally, each crewmember usually takes one bed of
lettuce to thin at a time, and works their way down to the end of the seedline and
the bed, then work their way back by thinning the seedline opposite of the one
they just finished thinning. The same process is done for lettuce beds with more
than 2 seedlines; however, crewmembers often will thin 2 to 3 seedlines on their
way down and 2 to 3 seedlines on the way back up from the bed, which makes the
process much slower per bed. For this experiment, the time taken by one crewmember to complete the entire process in a designated measured area was recorded with a stop watch. This process was continued until every crewmember was timed at least once. After the lettuce thinning process, each bed with a designated sub-plot was measured again for accuracy in the timings. All the data collected for each crewmember was combined to calculate the average timing for the entire crew and converted to an hour’s per acre basis. This process was done for each manually-thinned area. For plots thinned with an automated thinner, the time taken to thin the entire treatment plot was recorded from start to finish. Automated thinners were able to thin 2 to 4, 1.01 m (40 in) beds at a time, and one, 2.02 (80 in) bed at a time. Chemicals used to thin included carfentrazone (0.3 oz/acre), NpHuric (7gal/acre), and 14-0-0-5 fertilizer (13g/acre). The data was then converted to hours per acre.

One to 2 days after the lettuce thinning process, crop stand counts were taken again to evaluate how many plants were within each sub plot after the treatments were performed. Weed density by species was also recorded according to the methods described earlier. Doubles were also counted again after the thinning process. The spacing between each lettuce plant within a crop row was also measured in each sub-plot. This was done by measuring from the center of one plant to the center of the next plant with a measuring tape (Table 5).

Approximately 2 weeks after lettuce thinning, a crew again went through each treatment plot with hand hoes to remove doubles left behind and weeds which had emerged after the thinning process (Table 6). Again, the time taken to perform this action for each sub-plot was recorded using the same method described earlier and converted to a per acre basis.
Table 4. Dates of treatment applications in the various sites in 2014 and 2015.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Year</th>
<th>Automated Thinning</th>
<th>Manual Thinning</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2014</td>
<td>20-May</td>
<td>30-May</td>
</tr>
<tr>
<td>2</td>
<td>2014</td>
<td>9-May</td>
<td>22-May</td>
</tr>
<tr>
<td>3</td>
<td>2014</td>
<td>26-May</td>
<td>4-Jun</td>
</tr>
<tr>
<td>4</td>
<td>2014</td>
<td>11-Jun</td>
<td>24-Jun</td>
</tr>
<tr>
<td>5</td>
<td>2014</td>
<td>27-Jun</td>
<td>5-Jul</td>
</tr>
<tr>
<td>6</td>
<td>2014</td>
<td>18-Jun</td>
<td>24-Jun</td>
</tr>
<tr>
<td>7</td>
<td>2014</td>
<td>25-Jul</td>
<td>5-Aug</td>
</tr>
<tr>
<td>1</td>
<td>2015</td>
<td>15-Jun</td>
<td>22-Jun</td>
</tr>
<tr>
<td>2</td>
<td>2015</td>
<td>15-Jun</td>
<td>22-Jun</td>
</tr>
<tr>
<td>3</td>
<td>2015</td>
<td>15-Jun</td>
<td>22-Jun</td>
</tr>
<tr>
<td>4</td>
<td>2015</td>
<td>15-Jun</td>
<td>22-Jun</td>
</tr>
</tbody>
</table>
Table 5. Lettuce stand counts and weed evaluation dates in the treatment plots.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Year</th>
<th>Lettuce</th>
<th>Weeds</th>
<th>Doubles</th>
<th>Lettuce</th>
<th>Weeds</th>
<th>Doubles</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2014</td>
<td>35-May</td>
<td>23-May</td>
<td>23-May</td>
<td>29-May</td>
<td>29-May</td>
<td>29-May</td>
</tr>
<tr>
<td>2</td>
<td>2014</td>
<td>12-May</td>
<td>12-May</td>
<td>12-May</td>
<td>28-May</td>
<td>28-May</td>
<td>28-May</td>
</tr>
<tr>
<td>3</td>
<td>2014</td>
<td>4-Jun</td>
<td>4-Jun</td>
<td>4-Jun</td>
<td>5-Jun</td>
<td>5-Jun</td>
<td>5-Jun</td>
</tr>
<tr>
<td>5</td>
<td>2014</td>
<td>30-Jun</td>
<td>30-Jun</td>
<td>30-Jun</td>
<td>5-Jun</td>
<td>5-Jun</td>
<td>5-Jun</td>
</tr>
<tr>
<td>7</td>
<td>2014</td>
<td>31-Jul</td>
<td>31-Jul</td>
<td>31-Jul</td>
<td>6-Aug</td>
<td>6-Aug</td>
<td>6-Aug</td>
</tr>
</tbody>
</table>

1Automatically-thinned plots
2Manually-thinned plots
Table 6. Dates of double and weed removal.

<table>
<thead>
<tr>
<th>Site No.</th>
<th>Year</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2014</td>
<td>11-Jun</td>
</tr>
<tr>
<td>2</td>
<td>2014</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>2014</td>
<td>6-Jun</td>
</tr>
<tr>
<td>4</td>
<td>2014</td>
<td>9-Jul</td>
</tr>
<tr>
<td>5</td>
<td>2014</td>
<td>19-Jul</td>
</tr>
<tr>
<td>6</td>
<td>2014</td>
<td>9-Jul</td>
</tr>
<tr>
<td>7</td>
<td>2014</td>
<td>16-Aug</td>
</tr>
<tr>
<td>1</td>
<td>2015</td>
<td>3-Jul</td>
</tr>
<tr>
<td>2</td>
<td>2015</td>
<td>3-Jul</td>
</tr>
<tr>
<td>3</td>
<td>2015</td>
<td>3-Jul</td>
</tr>
<tr>
<td>4</td>
<td>2015</td>
<td>3-Jul</td>
</tr>
</tbody>
</table>

One day prior to or the day of crop harvest, the lettuce plants were evaluated for *S. minor* damage. During the 2014 season, this was performed by dividing each treatment plot into 9 sections. Within each section, 2 to 3 randomly chosen beds were selected for evaluation. In each of these beds, a 9.144 m (30 feet) section was measured, and each lettuce plant which was infected with *S. minor* in this section was visually inspected and recorded. This process was repeated for each of the 9 sections within each treatment plot. In the 2015 study, *S. minor* evaluations were performed within each of the 9.144 m (30 feet) sub-plots previously measured out to collect stand count, weed densities, and other evaluations previously described.
Lettuce growers in the Salinas Valley usually estimate crop yield based on number of 24 marketable lettuce plants per box. As mentioned earlier, in this study, the total weight of 24 random lettuce plants and the total weight of 24 marketable plants was estimated. In the 2015 study, total and marketable crop yields were also recorded for analysis as the varieties were similar. This was done by harvesting 24 whole lettuce plants from a sub-plot one to 2 days prior to, or the day of harvest. Within each subplot, an entire row of 12 lettuce plants were harvested from each adjacent crop row (Figure 17). All 24 plants were then weighed together to estimate total yield on a fresh weight basis. After the plants were weighed, each plant was inspected for blemishes and quality and separated to represent marketable heads and weighed again to estimate marketable yield (Figure 18). Data for total and marketable yields were also collected for the 2014 season. However, as the main objective in 2014 was to compare automated thinners with manual-thinning in regards to the thinning process, number of doubles and weed control, numerous varieties of lettuce were used during this season. Therefore, total and marketable yields for 2014 were not included in the statistical analysis or results section.

The number of unharvested lettuce plants per plot were also counted the day after the field was completely harvested. In the 2015 study, the same method was used to perform S. minor counts as described for the 2014 study.

**Experimental Design and Data Analysis**

The experimental design was a randomized complete block. In the 2014 study, each site was considered a block; thus, there were 7 blocks (replications). Each block was divided into 2 halves, as described earlier, and the treatments were randomly assigned to the plots. Within each treatment plot,
Figure 17. Example of how lettuce plants harvested for total and marketable weights were collected in 2015.

Figure 18. Lettuce plants weighed to estimate total yield for cripshhead lettuce (a), inspection and partitioning of the plants based on marketability (b), and weighed again to estimate for marketable yield (c).
6 to 10 randomly chosen sub-plots were designated for data collection, as described earlier. In 2015, the study was conducted only at one location in 4 blocks. Each block was evenly divided in half to make 2 treatment plots. Each plot was then randomly assigned one of the treatments. Each treatment plot had 4 designated sub-plots for data collection as described earlier.

Data was analyzed using analysis of variance (ANOVA) procedures using general linear model (GLM) procedures in SAS version 9.3. The year and locations were considered as random effects and the treatments were considered as the fixed effects. Interactions between year and treatment were also tested for the various parameters. Assumptions of ANOVA were first tested for all parameters measured to see if they were met using the Shapiro-Wilk’s test for normality and the Levene’s test for homogeneity at a variance of 0.05 level of significance. Data that failed to meet the assumptions of ANOVA were transformed using a log transformation process and reanalyzed. For those parameters on which ANOVA was conducted on log transformed data, i.e. weeds per acre and the time required to remove doubles, the means were back-transformed for presentation. Tukey’s honestly significant difference (HSD) test was used to separate the means whenever the ANOVA indicated a significant difference at a 0.05 level. Since there was no significant ($P > 0.05$) interaction between the year and any of the parameters measured, the data were combined for the 2 years and analyzed.
RESULTS AND DISCUSSION

Thin Timing

Automated thinners completed the lettuce thinning process almost 3 times quicker ($P < 0.0001$) than the manual-thinning process (Figure 19). On average the automated-thinners took 2 hours/acre to thin the lettuce plots, whereas manual-thinning took more than 7 hours/acre. The automated-thinner equipment pulled by a tractor travels at a speed of more than 2 miles per hour which can cover up to 18 seedlines at one time. A single crew member could thin at a speed of less than one mph and thin only one seedline at a time. Therefore, comparing the automated-thinner ran by a single crewmember to what one crew member manually thinning indicates a substantial difference between the two. However, most automated thinners have a small window of time to go into a field and thin, usually very early in the morning. This is to prevent chemical drift to non-target lettuce plants. Spraying a field early in the morning is a common practice in the Salinas Valley because later in the day wind speeds are usually very high because of the geographical location. Interestingly, the manual-thinning crews also usually spend the early mornings thinning lettuce fields and then clean fields later in the day also because of high winds. This is because the workers consider the lettuce thinning process to be a more physically demanding process and prefer doing this process when it is not windy. When wind speeds increase in the early to late afternoon hours, the crews prefer to clean the fields which they consider to be a less strenuous task than lettuce thinning.

The number of lettuce plants left in the plots after the thinning process was similar ($P = 0.3754$) between the automated and manually-thinned treatments (Figure 20). On an average, there were 33,662 plants/acre and 32,913 plants/acre, respectively in the automated and in the manually-thinned plots.
Figure 19. Average time required for lettuce thinning in the automated and manually-thinned plots. Bars with the different letters are significantly different at a 0.05 level according to Tukey’s Honestly Significant Difference test.

Figure 20. Average number of lettuce plants per acre in the automated and manually-thinned plots after the thinning process.
Number of Two-Closely Spaced Plants (Doubles)

Automated thinners left more \((P = 0.0007)\) doubles (2 closely-spaced lettuce plants) than manual-thinning during the thinning process. The number of doubles in the automated thinning plots was about 5 times more than that in the manually-thinned plots (Figure 21). This could be because of the limitations of the automated thinner’s ‘machine vision’ technology. As mentioned earlier, the infra-red cameras used by these implements are programmed to recognize the lettuce plants by the color reflected from the lettuce plants. This information is then relayed to the spraying mechanisms algorithm which calculates the plants that should be sprayed or not sprayed. The technology is not at a stage yet where the camera can define 2 plants which are in close proximity to one another. Instead, the camera recognizes these 2 plants as one large plant. Some of the algorithms used by the automated thinners’ sprayers are influenced by the size of the plant. That is, if the implement has the choice of keeping or eliminating 2 plants, it eliminates the smaller plant and keeps the larger plant. This is not the case in manually-thinned plots where the crew members make decisions on spacing and are better able to distinguish 2 closely-spaced plants. Although, this can be dependent on the experience of the crew member. Therefore, this is probably the primary reason for the occurrence of higher numbers of doubles left behind in the lettuce plots thinned with automated thinners.

Weed Control

Number of weeds left behind after the initial thinning process was similar \((P = 0.3249)\) between the automated and manually-thinned plots (Figure 22). As mentioned earlier, the evaluation of number of weeds was concentrated in a 2 in (5 cm) band on either side of and within the seedline (crop row). Both treatments left behind 650 to 750 weed seedlings or plants/acre suggesting that the machine was
Figure 21. Average number of doubles (2 closely-spaced plants) after lettuce thinning in the automated and manually-thinned plots. Bars with the different letters are significantly different at a 0.05 level according to Tukey’s Honestly Significant Difference test.

as efficient as the thinning crew in its recognition of weeds (Figure 22). It was observed that both the systems tended to leave behind weeds in close proximity to the lettuce plants. In the manually-thinned plots, this could also be because the crew members may have had difficulties observing small weed seedlings or the small weed seedlings may have been concealed by the canopy of the lettuce plants. Furthermore, crew members take great precaution in preventing damage to lettuce plants while thinning or removing weeds so as prevent losses in stand counts. Therefore, they hoe more delicately around lettuce plants and possibly not fully remove the roots from the soil at times. In the machine-thinned plots, the reason for weeds being missed could be because of the same reason for doubles being left behind. As discussed earlier, the infra-red camera cannot distinguish a weed from
a lettuce plant. So if a weed is in close proximity to the lettuce plant, the camera recognizes this as a large lettuce plant and does not spray it. Occasionally, an entire weed was left behind in the space a lettuce plant should have been. In both the systems, the most prominent weed species in terms of population were burning nettle (*Urtica urens*), common purslane (*Portulaca oleracea*), hairy nightshade (*Solanum physalifolium*), shepherd’s purse (*Capsella bursa-pastoris*), common groundsel (*Senecio vulgaris*), common mallow (*Malva neglecta*), annual sowthistle (*Sonchus oleraceus*), and some grass species that were too small to identify. However, there was no difference between the 2 thinning systems in the number of weeds, by species, left behind (data not shown). Therefore, it can be implied that the recognition of the weeds by machine was not influenced by the type of species occurring in the study plots. Some of these species of weed are in the Asteracea family. These weeds have been observed to germinate later than the other species.

![Figure 22](image.png)

Figure 22. Average number of weeds in the seedline (crop row) after lettuce thinning in the automated and manually-thinned plots. The bars represent back-transformed data after analysis.
Double and Weed Removal Timing

The crews took less ($P = 0.0493$) time to go through the plots to manually remove the doubles, the weeds initially left-behind, and the weeds that had emerged after the initial thinning process in the manually-thinned compared to the automated-thinning plots. The time taken for this process was approximately 90 minutes/acre more in the automated than in the manually-thinned plots (Figure 23). As discussed earlier, this was primarily because the automated thinners left behind more doubles than manual-thinning. However, judging by the high numbers of doubles left behind by the automated system (almost 5 times more than the manual-thinning), this time difference in the double removal was much lower than expected. In other words, the time required to remove the doubles was not 5-fold more in the automated thinning compared to the manually-thinned plots. As discussed earlier, this could be because the double removal process occurred later in the afternoon as this process is less physically demanding as the number of plants and weeds to be remove where lower compared to initial thinning.

![Figure 23. Average time required for post-thinning removal of the doubles and weeds in the automated and manually-thinned plots. The bars represent back-transformed data after analysis. Bars with the different letters are significantly different at a 0.05 level according to Tukey’s Honestly Significant Difference test.](image-url)
**Lettuce Plant Spacing**

The average spacing between 2 lettuce plants within a crop row was similar ($P = 0.7496$) between the 2 thinning systems. The average spacing in the automated and the manually-thinned systems was approximately 11 in (28 cm) and 11.2 in (28.4 cm), respectively (Figure 24). Much engineering in the automated lettuce thinners has been dedicated to the precision in maintaining desired plant spacing in the algorithms within the computer while thinning a lettuce crop. This was observed in this study by the precision of the machine in lettuce thinning and in maintaining the desired plant spacing. It was also interesting to note the accuracy of the crew in maintaining the desired spacing between plants. It was also the first time ever that these types of evaluations were performed in manually-thinned plots. Therefore, both methods of thinning were not only accurate in plant spacing but precise as well. As discussed earlier, the desired plant spacing between lettuce plants within a row is 9 to 11 in (23 to 28 cm).

![Figure 24. Average spacing between lettuce plants within a row in the automated and the manually-thinned plots.](image)
**Sclerotinia minor Counts**

The number of lettuce plants infected with *S. minor* was similar (*P = 0.9459*) between the automated and the manually-thinned plots. There were approximately 1000 lettuce plants/ac that was infected with *S. minor* at harvest in both thinning systems (Figure 25). Contrary to the assumption that there may be a greater number of lettuce plants infected with this fungus in manually-thinned plots because of the possibility of injuring and exposing the lettuce roots during the thinning process with hand hoes, this was not true.

![Figure 25. Average number of plants infected with *Sclerotinia minor* in the automated and manually-thinned plots.](image)

**Un-Harvested Lettuce Heads**

The number of un-harvested lettuce plants at the end of the study was similar (*P = 0.9701*) between the automated and the manually-thinned plots. In both the systems the average number of unharvested lettuce heads were approximately 1,200 plants/acre (Figure 26). If the lettuce heads at harvest are less than the desired size for market, the growers usually leave these plants un-
harvested in the field. This was an important parameter to consider in the verification of whether the automated thinning resulted in a greater number of smaller plants at harvest because of inadequate spacing of lettuce plants within a row during thinning. Conversely, if a crewmember had the choice between removing a smaller lettuce plant than a larger one, the person would generally choose to remove the smaller plant but if that plant was only a couple of centimeters away from optimal spacing, the crewmember would choose the smaller plant over the larger plant to keep spacing constant. These results support the earlier finding in similarity between the 2 systems in the within-row spacing between the lettuce plants.

![Figure 26](image)

**Figure 26.** Average number of un-harvested lettuce plants in the automated and manually-thinned plots after final harvest.

**Harvest Weights**

The average total weight of 24 lettuce plants was similar ($P = 0.8558$) between the automated and manually-thinned plots. The average weight of the 24 lettuce plants in both systems was approximately 25 kg (Figure 27). Similarly, the
weight of the 24 marketable lettuce heads also did not differ \((P = 0.8821)\) between the 2 systems with an average of approximately 17 kg (Figure 28). Therefore, the assumption that automated lettuce thinners would leave behind more small plants at thinning affecting size of lettuce heads and hence marketable yield did not hold true. Again, it is imperative that the accuracy and similarity in plant spacing within rows during thinning prevented such differences to occur in yield parameters.

Figure 27. Average total weight of 24 randomly selected lettuce heads from the automated and manually-thinned plots at final harvest in 2015.
Figure 28. Average weight of 24 randomly selected lettuce heads of marketable quality from the automated and manually-thinned plots at final harvest in 2015.
CONCLUSION

This study showed that automated lettuce thinners were comparable to manual-thinning in most of the parameter measured. The lettuce thinning process was achieved 3 to 4 times quicker with the automated system compared to the manual-thinning system. However, the automated system left more doubles in the plots in the thinning process. This resulted in approximately 90 minutes/acre more time required to remove these doubles in the post-thinning double and weed removal process compared to the manual thinning system. The automated system was as similar to the manual-thinning system in the initial weed removal process and the type of weed species did not influence the results. The automated system was as precise as the manual-thinning system in keeping the plants with a row at the desired spacing. This resulted in similar number of lettuce plants and number of un-harvested plants at final harvest in both systems which further resulted in similar total and marketable yield of the lettuce heads. Therefore, the automated thinners were very comparable with manual-thinning in efficacy and efficiency. Improvements, however, may need to be made in the automated thinner’s visual recognition process of doubles and weed species. Although this project determined many technical and production factors that are considered in adoption of precision automated lettuce thinning technology, an economic analysis is essential to provide more information to growers for widespread adoption of the technology.
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