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Review

A history of tillage in California's Central Valley

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ABSTRACT

The Central Valley (CV) of California is a remarkably productive agricultural region. Much of the productive capacity of the CV stems from the reliable tillage management systems that were developed beginning in the 1930s and that changed very little until the 1990s and even more dramatically in the 2000s. A variety of technologies, people and social networks have contributed to the major transformations in tillage management that have rapidly occurred during this recent time. Factors that influenced the prior slow evolution of tillage systems in the region include the need to find ways to farm with irrigation, cope with a broad range of soils, achieve high crop quality and yields to compete on world markets, expand farming operations to greater acreage, and find ways to farm with ever-increasing costs. The cost increases, recognition of the emerging concepts of conservation agriculture (CA), and the development and broader adoption of advanced irrigation systems are now spurring farmers and research organizations in the CV to overcome problems experienced with conventional tillage practices and to develop new cropping systems in the region including no-tillage and strip-tillage. Ultimately, broader adoption of conservation agriculture principles and practices in this region will stem from a diverse and complex set of motivating factors. The role of global farmer-to-farmer communication has had a major impact on this process. Ongoing targeted problem-solving efforts addressing weed, water and fertility management in conservation agriculture systems will be needed to make them more reliable and widely used.

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1. Introduction

1.1. Background

Tillage – the physical manipulation or disturbance of the soil for the purpose of crop production (Koller, 2003; Reicosky and Allmaras, 2003) – is an important aspect of agroecosystems that dates back to the very dawn of agriculture (Lal et al., 2007; Huggins and Reganold, 2008). While natural terrestrial ecosystems do not typically involve tillage (Beck, 2014), the majority of agro-ecosystems have been developed to include some measure of tillage or soil manipulation as part of their sustained success in producing crops. Over the ages, farmers have relied on tillage operations in their fields to achieve a variety of functions that contribute to and improve crop productivity (See Box 1). These fundamental and universal goals of tillage have been used around the world across a great range of production scales and have variously employed human, animal or mechanical energy sources depending on a farmer's means and access to technology. Some of these goals of tillage, however, need to be reevaluated as we increase our understanding of agro-ecosystems.

The recorded history of the development of tillage practices used in various regions of the world is both fascinating and complex (Coughenour and Chamala, 2000; Lindwall and Sonntag, 2010; Awada et al., 2014; Duiker and Thomason, 2014; Brock et al., 2000). During the last thirty years of the twentieth century, a number of relatively radical tillage system alternatives including no-tillage and strip-tillage have become common and more widely adopted around the world (Lindwall and Sonntag, 2010; Reicosky and Allamaras, 2003). These systems that are now known as a key component of an expanded system called "conservation agriculture" (see Box 2) have been critical to the agricultural sustainability of several regions including the US Great Plains (Morrison, 2000), the central Canadian plains (Lindwall and Sonntag, 2010; Awada et al., 2014), much of Brazil, Argentina and Paraguay (Derpsch and Friedrich, 2009; Junior et al., 2012), and Western Australia (Crabtree, 2010; Llewellyn et al., 2012). The spiral of soil improvement and water conservation afforded by changes from conventional tillage management approaches to no-tillage, high-residue systems throughout the Dakotas and Nebraska, for instance, are widely credited with reversing the downward economic trend of farms in that region in the 1990s with not only enabling the diversification and intensification of the productive capacity, but also sustaining the economic viability of farming in this part of the country (Anderson, 2005, 2009, 2011). The largely farmer-led innovations that began in the 1970s in South America also involved conversion to no-tillage over the majority of farmland in Brazil, Argentina and Paraguay (Junior et al., 2012; Friedrich and Kassam, 2011). Likewise, the innovations were largely credited with reversing the unsustainable soil losses due to erosion throughout that region and contributing to lowering production costs (de Freitas and Landers, 2014). The simultaneous expansion of no-tillage adoption in Western Australia (Friedrich et al., 2012; Llewellyn et al., 2012) and Canada (Lindwall and Sonntag, 2010; Awada et al., 2014) is another example of local, largely farmer-initiated innovation in tillage management that went far in assuring the sustainability of farming in these regions.

The technologies, people and social networks that have led to each of these major tillage system transformations across these wide-ranging regions have been captured, archived and showcased for various audiences in a variety of historical accounts (Coughenour and Chamala, 2000; Junior et al., 2012; Kassam et al., 2014a, b; Lindwall and Sonntag, 2010; Awada et al., 2014) and formats (http://www.kis.usask.ca/CTConference.html#Dumanski). Tillage innovation is thus an important way in which agriculture improves and becomes more efficient and sustainable. Understanding experiences with tillage system innovation and how mindsets change as new systems are adopted is also important because it provides information of the huge challenges that will be required to achieve further timely transformational changes in agricultural production systems (Lindwall and Sonntag, 2010; Awada et al., 2014). Because no comprehensive historical archiving of tillage system and management changes in California's Central Valley (CV) (Fig. 1) exists and because of the dynamic evolution and

Box 1. Functions of tillage

To create a seedbed
To loosen compacted soil layers
For weed, insect, and pathogen control
For aeration
To incorporate crop and weed residues into the soil
To inject or incorporate fertilizers and pesticides
To facilitate irrigation, water infiltration and soil moisture storage
To stimulate net nitrogen mineralization
To plant a seed/seedling
For rain capture
To control soil temperature
For salinity control
To mix soil layers
To increase rooting

Box 2. Conservation agriculture

The Food and Agriculture Organization (FAO) of the United Nations defines conservation agriculture (CA) as an "approach to managing agroecosystems for improved and sustained productivity, increased profits and food security while preserving and enhancing the resource base and the environment (http://www.fao.org/ag/ca/1a.html) ". CA has three linked principles, namely

- Continuous minimum mechanical soil disturbance,
- Preservation of residues that provide permanent soil cover,
- Diversification of crop rotations.

The FAO further describes CA as universally applicable to all agricultural landscapes and land uses with locally adapted practices (Kassam et al., 2014a; Kassam et al., 2014b). CA is gaining acceptance in many parts of the world as an alternative to both conventional agriculture and organic agriculture (Dumanski et al., 2014a,b). Some of this acceptance is due to improved emphasis on carbon (C) management. Conservation is more about plant and C management than soil management. The acceptance of the synergistic simplicity of no-tillage (minimizes C and soil loss) and the use of diverse rotations and cover crop mixes (maximizes soil coverage and C input) allows for soil diversity protection and regeneration. California's Conservation Agriculture Systems Innovation (CASI) Center works to develop information on locally-relevant adaptations of CA systems that also include the use of cover crops, integrated pest management, precision irrigation and controlled or limited mechanical traffic over the soil. An estimated 124,794,840 ha of arable cropland are currently farmed using CA principles with nearly half of this area in South America (Kassam et al., 2014a,b).

considerable innovations that have recently been associated with the development of improved tillage practices in the Valley, we investigated the recent history of tillage management systems in this region using a broad search of relevant literature coupled with extensive interviews with farmers who themselves have seen and made considerable changes in tillage practices over many decades in the Valley. Our goal was to capture and compile important transformative progress, people, and achievements that have been made and that have contributed to improved tillage systems in the region. We report this historical summary here.

1.2. The broad context of changing tillage systems

The transformational changes that have occurred in tillage management in the Central Valley of California during the past century have not come easily or quickly. The shift from conventional or standard tillage, which is traditionally defined as the sequence of operations most commonly or historically used in a given field to prepare a seedbed and produce a given crop, to a variety of new tillage system alternatives, provides an example of how significant cropping systems adaptation and change occur. Economic pressures throughout this period clearly weighed heavily on these evolutions in how basic farming was done, since new technologies are not adopted if they are not profitable. As in many other regions of the world where new tillage approaches have been adopted, economics alone do not explain the mindset shifts that eventually brought about changes in tillage practices (Lindwall and Sonntag, 2010; Awada et al., 2014). This review of the history of tillage management in California will therefore document how innovation in this aspect of Central Valley agriculture occurred as a result of economic, technological, social and psychological forces. We show how the rapid and transformative advances in tillage approaches that have occurred in California during the past fifteen years have created a new 'status quo' and resulted in a number of different factors and people coming together to bring about transformative change.

1.3. Qualitative methodology

To compile this history, a number of qualitative research techniques were used including searches of published documents of the University of California's Cooperative Extension, the University's quarterly research journal, *California Agriculture*, the has been published for 69 years, the Online Archives of California general database, and a number of the agricultural records maintained by the Special Collections Library at the University of California, Davis and California State University, Fresno. In addition, we conducted a survey of 307 Central Valley farmers regarding their familiarity with and use of different tillage systems (Bossange, 2014), and finally, in-person semi-structured and open-format interviews with three senior San Joaquin Valley (SJV) farmers regarding their recollections of tillage systems that were common during the middle and second half of the 20th century. Sample questions used in these interview are provided in Box 4. We also conducted biennial surveys of tillage management trends in the Valley since 2004 (http://casi.ucanr.edu/) that are similar in format to the National Crop Residue Management Surveys conducted by the Conservation Technology Information Center (http://www.ctic.purdue.edu/CRM/) and that have tracked the types of systems that are used for a range of historically dominant

Fig. 1. Location of California's Central Valley in the western United States.

crops throughout the region. In each of these investigations, our goal was to ascertain the sequence of practices that typically constituted the dominant tillage management system(s) for a given era and cropping context. For a number of reasons, including our inability to secure information or data prior to the 1930s, we constrained our inquiries and investigations from that starting point through today.

1.4. Clarifying tillage jargon

A challenge exists in clarifying the historical evolution of tillage systems in California and in terms of how some existing systems have transitioned to more complex conservation agriculture systems that use no-tillage. Tillage equipment developed and widely used in California over the past 30 years has served several different functions and has broadly become known as "minimum tillage" (Mitchell et al., 2009). Use of the term "minimum tillage" often does not provide quantitative information on tillage intensity or the degree of soil and residue mixing. Minimum tillage practices typically result in soil disturbance similar to conventional practices. They may, however, be considered to result in less overall soil inversion disturbance than would be expected with moldboard plow tillage. In addition, one of the most confusing issues is a local use of jargon terms that are not universally understood. Thus, at the beginning of this investigation of the evolution of California tillage systems, there is a need to clarify the often inconsistent and even contradictory terminology in discussions of tillage practices (Derpsch et al., 2014). In Box 3, definitions of tillage systems that have been standardized by California's CASI (Conservation Agriculture Systems Innovation) Center in accordance with international efforts also aimed at standardizing tillage system language and methodologies are provided. Whereas the term "conservation tillage" has been used to indicate a very wide range of reduced or so-called minimum tillage alternatives relative to conventional tillage approaches for a given region, Reicosky (2015) has pointed out that not only is the term "conservation tillage" (CT) an oxymoron, but it has also construed very mixed and confusing messages about CT as "good" tillage. Conservation tillage is better than intensive conventional tillage, but in many respects, it may not be good enough for long-term sustainability (Reicosky, 2015). Thus, the general concept and set of principles of the broader term, "conservation agriculture," that generally involves principles of no-tillage seeding, the preservation of surface residues, and also diversity of crop rotation and use of cover crops (Derpsch and Friedrich, 2009) better represents the long-term system goals that are being developed and evaluated in many parts of the world as a potential strategy for "sustainable intensification" of agricultural productivity. This term is defined as "the process of delivering more safe, nutritious food per unit of input resource, while allowing the current generation to

Box 3. Glossary of tillage terminology

A fair amount of jargon exists and is used related to tillage terminology. In an effort to clarify and to standardize nomenclature, the Conservation Agriculture Systems Center (http://casi.ucanr.edu/) has outlined the following general categories of tillage systems. Additional information and more complete definitions may be found in UC ANR Publication 8364 (Mitchell et al., 2009; SSSA, 2008; ASABE, 2011a,b).

Standard or conventional tillage

The sequence of operations most commonly or historically used in a given field to prepare a seedbed and produce a given crop

Minimum tillage

This term has been adopted by the Conservation Tillage Workgroup as a subcategory of conservation tillage. It refers to systems that reduce tillage passes and thereby conserve fuel use for a given crop by at least 40 percent relative to what was conventionally done in the year 2000.

No-tillage

In no-tillage or direct seeding systems, the soil is left undisturbed from harvest to planting except for injection of seed and fertilizers.

Strip-tillage

With strip-tillage, the seed row is tilled prior to planting to allow residue removal, soil drying and warming, and in some cases subsoiling to a depth of 8 to 12 inches. With both no-tillage and strip-tillage, typically less than one-third of the soil surface is disturbed.

Ridge-tillage

In ridge-tillage, the soil is also generally undisturbed from harvest to planting except for fertilizer injection. Crops are seeded and grown on ridges or shallow beds that are formed or built during the prior growing season, generally during cultivation using implements fitted with sweeps, hilling disks, and furrowing wings.

Mulch-tillage

Mulch-tillage, the fourth major CT category, includes any CT system other than no-tillage, strip-tillage, or ridge-tillage that preserves 30 percent or more surface residues. Mulch-tillage uses conventional broadcast tillage implements such as disks, chisel plows, rod weeders, or cultivators, but with limited passes across a field so as to maintain plant residue on the soil surface year-round.

Conservation Tillage

Conservation tillage has been used as a "collective umbrella term" that denotes practices that have a conservation goal of some nature. The term "conservation tillage" broadly encompasses tillage practices that reduce the volume of soil disturbed, preserve rather than incorporate surface residues, and result in the broad protection of resources while crops are grown. California's Conservation Agricultural Systems Innovation Center originally defined conservation tillage as including the 'classic' forms of CT, -no-till, strip-till, ridge-till and mulch till, that preserve 30 or more percent of the soil surface covered by residues after planting, and minimum tillage systems that reduce tillage passes by 40 or more percent. However, now CASI prefers to use the term "conservation agriculture" because the phrase "conservation tillage" is, as Reicosky has suggested, an oxymoron. Any form of intensive tillage is not a form of conservation for the way intensive tillage degrades and fractures the natural soil structure.

Controlled Traffic Farming

Controlled traffic farming (CTF) maintains the same machinery wheel tracks in cropping fields year after year. It relies on integrating machinery so all field traffic travels on the smallest number and area of permanent traffic lanes. It uses machinery in an organized and precise way to increase productivity by minimizing the area of soil damaged by compaction.

meet its needs without compromising the ability of future generations to meet their own needs" (Smith, 2012).

1.5. Evolution of tillage in Central Valley

Many factors drive the evolution of agricultural soil tillage systems including, but not limited to, climate, soils, water availability, farmer experience, labor, knowledge, energy and markets. Tradition within the California CV was less a factor in tillage development than efforts to find ways to farm with irrigation, cope with fine-textured, cracking soils with low organic matter, achieve high crop quality and yields to compete in national or world markets, expand farming operations to greater acreage, and find ways to farm with ever-increasing costs. Irrigation played a large role since it had to be managed with soil modification or tillage to level fields, create furrows and borders, and as a means for water delivery. Family farms, although they existed, tended to not be the model. The corporate farm, even if within a single family, with a profit motive rather than a survival motive, thus drove the development of tillage, and as a consequence, not all changes or decisions were consistent with sustainability. As tractors replaced horses, they introduced narrow, continuous soil compactions zones or ribbons that resulted in the need for increased tillage operations to minimize the uneven effect of tractor wheels and tracks on irrigation and planting. With animal power the compacted zones were random allowing lateral water infiltration and root exploration around compacted zones. As the evolution included higher horsepower tractors with weights exceeding 100% of intended draft, the zones of compaction increased in size and depth. During this same period, mechanized harvesting machines continually increased in size and weight. Recognizing the deleterious effect of this compaction, farmers sought deeper tillage tools that eventually included harrows with greater than 15 cm working depths, chisels capable of a 30 cm depth of penetration, subsoilers for depths exceeding 60 cm, as well as massive turning plows. Machinery companies created manufacturing plants for the special needs of California: Killefer in the Los Angeles area (John Deere), Stockton Works in Stockton (International Harvester), Globe Disk in Ventura (Case) and others. This destructive cycle of increased compaction, increased tillage, and increased cost characterized California field crop agricultural systems during much of the second half of the 20th century. Ironically yields and profits were increasing and the system was adopted by others countries, including Israel and Australia. With costs increasing and recognition of the emerging concepts of conservation agriculture and the development of advanced irrigation systems, many leading farmers and research organizations committed to discover methods to overcome the problems experienced with this death spiral evolution created by mechanization.

1.6. Early history of tillage management in the San Joaquin Valley's west side

Despite thorough reviews and histories of the introductions of various agricultural machines including tractors and harvesting equipment in California (Dunning, 1999) and around the world (Reeder, 2000; Owen, 2001; Freebairn et al., 1993), no comprehensive record is available about the specific tillage or intercrop soil disturbance practices that have been generally employed in a given region of the state for a particular crop at a specific time, with the exception of the 1975 comparison of tillage systems for cotton by Abernathy et al. (1975). Thus, to compile such a history for the past hundred years, we began by conducting interviews with several retired CV farmers, equipment entrepreneurs, and researchers whose ages averaged about 97 years and who represented a rich and deep familiarity with these practices over their lifetimes. Each interview was conducted in their business or farm offices, covered about 90 min, and included a range of prepared as well as more open-ended questions similar to those listed in Box 4. From these interviews, a number of common conclusions may be made.

Prior to the 1930s, the vast majority of farmers in the region used dryland farming techniques that involved mule or horse-drawn grain drills for crops such as wheat and barley. "You would just drill it in, and pray a lot," recalled Jack Woolf, who worked for much of the early part of his career for the large Giffen Ranch farm that consisted of over 48,562 ha in the southern West Side region of the SJV. Later he established his own family farm, Woolf Farming, in the town of Huron in western Fresno County. Dryland grain farming during that era involved little more than "tickling the surface of the land" with a relatively shallow disking operation and waiting for rain, Woolf reported.

The 1930s and the introduction and expansion of well drilling and water pumping marked a major turning point for farming in the region because more reliable and accessible irrigation water became available. "The introduction of turbine pumps," Woolf recounts, "made possible the development of West Side CV farming." In that era, the pumps were "going like mad" and the increased production that was afforded by irrigation served to supply the growing need for more diverse crops like cotton, flax and a range of small grains during the World War II (WWII) era and beyond. Tillage equipment during the early decades of the twentieth century was quite rudimentary and fit into what was often the equivalent of a typical summer fallow. Fields were fallowed for one summer growing season and then followed by an annual crop the next year. This system allowed for precipitation to be captured and stored, and enabled another crop in the third year. Thus, barley/summer fallow and cotton/summer fallow were common strategies during this period with only a light or shallow disking to 'go after the weeds' at key intervention points in a rotation. It was also during this post-WWII period in the early 1950s when an array of farm chemicals were introduced. Land planing was more widely adopted and added to a farm's tillage program to "get rid of knobs and to flatten out low spots" (J. Woolf, personal communication,) which could then make both cross-check surface flood and sprinkler irrigation easier and more uniform.

While it is difficult to generalize specific tillage protocols that were used broadly throughout a region, interviews with farmers who have recollections of the practices during this early period agree that the tillage tools and practices used during this era were

Box 4. Types of general questions used in surveys of Central Valley farmers regarding their tillage practices

How do today's tillage practices compare with what was commonly done 40 or 50 years ago?
How has your use of tillage equipment changed over this period?
Have there been changes in the size of tillage equipment and tractors that you've used during these years?
Have there been changes in the amount of fuel use that is associated with your tillage implements?

remarkably similar and that much of the 1900s may well be described as a "century of standard tillage" (J. Woolf, personal communication). Soil tillage, or "land preparation" operations during much of the twentieth century thus typically consisted of disking using a disk plow, subsoiling to about 60 cm to break up subsoil compaction, plowing, landplaning and listing or pulling planting bed ridges through a field ahead of seeding. Some modification of this basic litany of tillage operations typified most annual crop fields during most of the 1900s throughout Central Valley annual cropping systems.

1.7. Mid-20th century innovations

This period of the 20th century witnessed challenges in several parts of the world to the conventional tillage techniques that had become common during this time but that were beginning to show weaknesses and problems. As early as 1943, when Edward Faulkner published Plowman's Folly, a controversial book that led to one of the most engaged debates on agricultural practices in the entire last century (Personal communication, Touchton), the potentially destructive impacts of intensive conventional tillage were exposed. Severe soil loss to erosion was implicated with tillage practices, that was a concern in many agricultural production areas, provided impetus for the creation of soil conservation movements and the ultimate development of "conservation tillage" systems that subsequently occurred in many parts of the world (Personal communication, Touchton).

There were also a number of noteworthy introductions of innovative tillage equipment being developed in the Valley. These introductions ended up not becoming part of the dominant production paradigms that tended to persist in most annual crop production contexts. One remarkable equipment innovation introduced in California was the Shredder Bedder, a one-pass implement that shredded, undercut cotton stalks, and reshaped planting beds following harvest. This implement was invented by Al Ruozi of Bakersfield, CA (Interstate Mfg) in the mid-1950s (Photo 1). Born in 1917, Ruozi grew up and worked with farm machinery his entire life and created this machine that was patented, then tested and certified by the USDA Agricultural Research Service Soil Dynamics Laboratory in Auburn, AL for pink bollworm (an over-

Photo 1. Shredder-Bedder (Interstate Mfg., Bakersfield, CA), a one-pass cotton postharvest rebidding implement designed and developed by Al Rouzi, 1958 (Photo: A. Rouzi).

wintering cotton pest) control in Brawley, CA in 1967 and 1968. This machine was a more efficient alternative to conventional cotton postharvest tillage and achieved stalk management practices that were in full compliance with the state's pink bollworm eradication program. This Shredder Bedder was in many ways an example of an introduction of technology that was clearly "well ahead of its time". This was because, although it worked well and was used on some cotton farms, primarily in Kern County, CA, it did not achieve widespread adoption or use at that time.

Then, beginning in the early 1960s and extending into the 2000s, Lyle Carter and his research team at the USDA-ARS Cotton Research Station in Shafter, CA contributed greatly to the evolution of tillage systems for CV crops. The goal of Carter's work was to evaluate and develop what are now broadly known as "minimum tillage" systems that he defined as the "least number of field operations required to accomplish proper soil physical conditions for seed germination and root development." (Carter and Stockton, 1963).

Most tillage strategies during this period commonly used seedbed preparation approaches involving seven or more trips across the field, i.e. shredding residues, disking twice using a disk plow, plowing, disking, harrowing or floating, bedding, and mulching (Carter and Colwick, 1971). Most operations following plowing tended to recompact the soil ahead of planting. If loosening the soil for root and water penetration, however, is the main objective of tillage, such broadcast tillage systems, Carter reasoned, would seem to be inefficient. His work thus evaluated what he first termed "precision tillage" (Carter and Colwick, 1971) and later "zone production systems" (Carter et al., 1991) that would provide a suitable root zone in contrast to broadcast tillage in which the specific area of root development is not considered (Carter et al., 1965). This early work of Carter showed that precision tillage or subsoiling directly under the intended seed row and bedding up in the same operation (Carter et al., 1965) was effective in increasing cotton yields in soils where root growth is inhibited by soil compaction. The precision tillage concept that Carter pioneered in the SJV resulted in lower penetration resistance in the seed row and a 60% reduction in total energy requirements (Carter and Stockton, 1963). Both the theoretical and applied basis for the minimum tillage concept were developed in the Valley at the close of the twentieth century. Carter was also the first researcher in California to couple zone production, controlled traffic systems with a wide tractive vehicle (Carter et al., 1988) that reduced primary tillage production costs. Controlled traffic farming (CTF) is a traffic management system that combines all wheel traffic to the smallest wheel tracks within a field for crop growth zones that are kept separate from traffic zones (Kingwell and Fuchsbichler, 2011; Gasso et al., 2013, 2014). Carter's work in the CV was some of the earliest CTF research and development work that has expanded in several areas of the world in recent years (Tullberg et al., 2007). His observation that "there is no need for tillage unless it is to correct a problem that you have created," continues to be an important guidepost for tillage and CA systems research and development in the Valley.

1.8. No-tillage adoption in California dryland systems

No-tillage seeding of small grains such as wheat and barley started in the mid-to late-1980s in dryland crop production regions of California including the Sacramento Valley, the southeastern SJV and in the Carrizo Plains area of San Luis Obispo County in the mid-to late-1980s (Pettygrove et al., 1995). These efforts were inspired by experiences that farmers in Western Australia had during the early 1980s with similar dryland seeding approaches. A number of California dryland farmers had received knowledge and support during this time from no-till farmers in eastern Washington who came to California with their no-till drills to provide custom seeding services for California farmers. Dryland or rainfed production of small grain crops in these regions of California relied on an entire year of fallowing to acquire sufficient soil moisture to justify seeding. Farmers who attempted no-tillage seeding during this time emphasized three primary benefits: (a) no-till seeding increased water infiltration and storage in the soil; thereby, in theory, enabling continuous cropping without fallows;

Photo 2. No-till dryland seeding of barley at Yolo County farm of Fritz Durst, 2012 (Photo: J. Mitchell).

(b) reduced soil erosion; and (c) substituting herbicides for disking or cultivation increased speed over the fields and also reduced machinery and labor costs (Klonsky et al., 1994).

Fritz Durst, a very early adopter of no-tillage dryland seeding in Yolo County, noted at a field day at his farm that, once he had begun using no-till techniques, his pond no longer had water in it due to increased soil aggregate stability, water infiltration, and water storage that resulted from reduced soil disturbance and surface residue preservation (Personal communication, S. Pettygrove) (Photo 2). While attempts were made by both farmers, such as Durst and fellow Yolo County, no-till innovator, Charlie Rominger, and by University of California Cooperative Extension Advisors and NRCS conservationists, most dryland no-tillage small grain production disappeared due to lack of predictable rainfall for crop establishment, difficulties in getting seed deep enough for germination, and economic yields to offset costs (Klonsky et al., 1994).

In addition to these early efforts, two private sector entrepreneurs, Bill Kellogg and Ralph Cesena, Sr. worked with farmers throughout the Valley to develop and refine seeding options with less tillage. Kellogg's Ag Services introduced and provided several different no-till drills for rent that have been available to farmers primarily in the Sacramento Valley for more than thirty years. Also beginning in the 1980s, Ralph Cesena, Sr. out of Stockton, CA worked with several south Sacramento Valley and north San Joaquin Valley farmers on a variety of no-till, ridge-till and strip-till systems for crops such as corn, wheat, beans, and tomatoes. Cesena was the regional distributor for Buffalo Mfg. (Fleischer, NE) which marketed a broad line of no-till (sweep blade) and ridge-till seeders and ridging cultivators that theoretically seemed to be well suited for the furrow irrigation systems that were in use (Photo 3). Ridge-till offered an annual crop production system alternative that used one-pass seeders equipped with front-mounted sweeps ahead of the planting shoe that could establish crops into a prior season's surface residues and then use in-season high residue ridging cultivators to push soil up around the plant row thereby also creating cleaned out furrows for irrigation water movement. The work of Kellogg and Cesena, and for that matter, also of Ruozi earlier in the century provided early exposure and 'proof of concept' demonstrations of new approaches, new crop establishment equipment, and new paradigms for how farming systems might function. It did not, however, lead to much actual adoption of these techniques. While the direct uptake of the introductions that these three innovators made may appear limited across today's landscape, their contributions providing alternatives and encouraging the eventual evolution of reduced disturbance tillage systems that is now taking place in California have been quite significant.

1.9. Two decades of accelerated change—1990s–2000s

Unprecedented changes in tillage management in California have occurred in the last two decades (Fig. 2) due to a number of factors (Table 1). One of the two greatest transformations in tillage practices during this period has been a dramatic increase in the

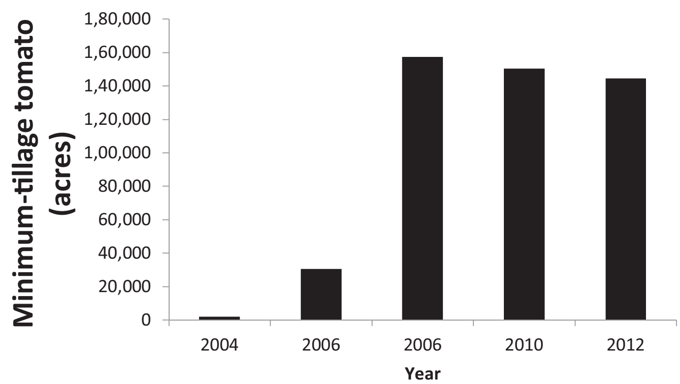

Fig. 2. Minimum tillage acres in California's Central Valley counties including Kern, Tulare, Kings, Fresno, Madera, Merced, Stanislaus, San Joaquin, Sacramento, and Yolo, from 2004 to 2012.

Photo 3. Ralph Cesena, Sr. (right), private sector consultant on no-till and ridge-till seeding systems with Denair, CA farmer, Darrell Cordova, 2006, (Photo: J.Mitchell).

Table 1
Major factors contributing to changes in tillage management in California from 1990 to 2014.

- Increasing production costs
- Availability of glyphosate herbicide and genetically-modified seed
- Increased in fuel costs
- Air quality improvement mandates that incentivized reductions in tillage-induced dust generation
- Introductions of new equipment
- Farmer innovation and local clusters of tillage innovation
- Tillage implement research and development successes
- Availability of NRCS Environmental Quality Incentives Program cost-share support targeting air quality improvement goals
- Drip irrigation

Photo 4. Reworking beds with the minimum tillage, pass-combining Performer implement (Wilcox Agriproducts, Walnut Grove, CA), 2014, (Photo: A.Wilcox).

adoption of minimum tillage, or "pass combining" systems that include a variety of tillage tools on a single implement thereby reducing the need to pass over a field multiple times (Photos 3 and 4). "Min till" approaches still largely achieve full surface soil disturbance to a typical depth of 20–30 cm as occurs with conventional tillage, but they do so with considerably fewer tillage passes across a field by combining tillage tools on a single implement (Mitchell et al., 2004). Two general types of minimum

Photo 5. Non-bed-preserving pass-combining tillage using the Optimizer (Tillage International, Turlock, CA), 2014 (Photo: K. McDonald).

tillage equipment have been introduced since the early 1990's. "Permanent or semi-permanent bed" minimum tillage implements such as the Sundance Wide Bed Disk (Arizona Drip Systems, Coolidge, AZ) the Hahn PermaBed Disk (Hahn Tractor, Stockton, CA), and the Wilcox Agriproducts Performer (Walnut Grove, CA) (Photo 4) till existing beds and leave them in place. These implements are generally used with GPS-guidance steering systems to preserve planting beds and traffic furrows in true "zone tillage" fashion, a term originally coined in 1985 (Carter, 1985; Carter et al., 1987, 1991). These "bed-preserving" systems are commonly and widelyl used with subsurface drip irrigation beds, and particularly for tomato production which now has a very high proportion of drip irrigation. Since 1980, the land area for tomato production under drip irrigation has increased from 0 to over 90% in 2014 (Mitchell et al., 2012b).

The second type of minimum tillage approach that is typified by the Wilcox Agriproducts Eliminator (Walnut Grove, CA) (Photo 5) or the New World Tillage Incorporated's Optimizer (Modesto, CA) (Photo 6), does not preserve dedicated planting beds, but rather broadcast tills a field while mixing and incorporating residues and preparing seedbed tilt in a single pass. With any of the minimum tillage implements, tillage operations are combined, fewer passes across a field are required and less deep or vertical tillage is generally performed. However, the extent of horizontal or shallow surface tillage that is performed is generally similar to conventional tillage systems. Because these "minimum tillage" approaches reduce the total number of tillage operations, fuel usage is also reduced (Upadhyaya et al., 2001). An average fuel saving of 50% and a time saving of 72% have been reported with one-pass tillage equipment (previously known as the "Incorpramaster," but now known as the "Optimizer," (Tillage International, Modesto, CA)) compared with the standard tillage program of disking and landplaning in the Sacramento Valley (Upadhyaya et al., 2001). Additionally, recent investigations using advanced atmospheric light detection and ranging measurement techniques conducted in Los Banos, CA, showed this combined-operations minimum tillage method reduced 2.5-μm (0.0025 mm) particulate matter emissions by 29%, 10-μm (0.0010 mm) particulate matter by 60%, and time and fuel per acre by 40% and 50%, respectively, compared with standard methods (Moore et al., 2013).

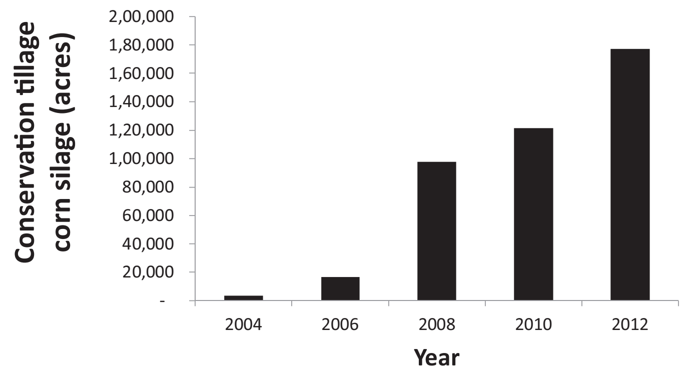

Fig. 3. Changes in Central Valley, California dairy silage acreage under strip-tillage and no-tillage, 2004–2012.

1.10. No-tillage and strip-tillage silage production

Another cropping sector that has transformed its basic tillage practices during the past decade, is dairy silage production. No-tillage and strip-tillage corn, for example, increased from 1414 ha or about 1.0% of total corn silage production acreage in 2004, to 71,718 ha, or roughly 37.5% of total acreage in 2012 (http://casi.ucanr.edu/?blogpost=15475&blogasset=14128) (Fig. 3). Strip-tillage corn production makes up the bulk of this acreage. It is now typically accomplished with one strip-tillage pass following winter wheat or triticale to loosen subsoil layers and to prepare a seedbed before a surface-applied preirrigation which is then followed by corn seeding. The use of strip-tillage, with any of a number of commercially-available implements such as the 1-tRIPr (Orthman

Photo 6. Strip-tillage and seeding operations conducted by California Ag Solutions, (Madera, CA) with Central Valley dairy silage farmers who are interested in learning about strip-tillage, 2014, (Photo: M. Bottens).

Mfg., Lexington, NE), the Bigham Brothers Strip-Tiller (Lubbock, TX), or the Till-N-Plant 2 (Schlagel Mfg., Torrington, WY) typically eliminates five to ten or even more tillage passes and roughly $70 per acre for fuel and labor from silage corn production compared to traditional or standard tillage operations. Strip-tillage has also reduced particulate emissions of dairy silage corn production by 60–80% compared to traditional preplant tillage systems (Madden et al., 2008; Marchant et al., 2011), and overall production costs for tomatoes by $60 per acre (Mitchell et al., 2012a,b). As of 2014, commercial strip-till and corn planting support is now available to help farmers learn about these silage production systems. This program has been successful in providing learning opportunities to farmers interested in the adoption of strip-tillage practices and in increasing use of this tillage system in California (Photo 6).

2. Conservation Agriculture Systems Innovation (CASI) Center

In 1998, a small group of farmers, university researchers and cooperative extension educators, NRCS conservationists, and private sector partners formed the Conservation Tillage Workgroup to accelerate the development and adoption of tillage system alternatives for California's diverse crop production. This grassroots effort has been instrumental as a clearinghouse for information and in promoting the expanded adoption of conservation agriculture systems in California (http://casi.ucanr.edu/?blogpost=15475&blogasset=14128). Since its formation, it has grown to over 2100 members with focus not only on tillage practices, but to the development of conservation agriculture systems for California's Mediterranean climate with its diverse, irrigated and high value cropping. With its systems emphasis and its dedicated attention to the integrated goals of conservation agriculture as a means for improving California's agricultural systems, the original "CT Workgroup" has now expanded into the Conservation Agriculture Systems Innovation (CASI) Center which is a founding member of the North American Conservation Agriculture Systems Alliance (http://www.ctic.purdue.edu/Conservation%20Agriculture%20Systems%20Alliance/CASA%20Organizations/) and also of the Western States High Residue Irrigated Agriculture Consortium (http://irrigatedag.wsu.edu/tag/hrf/). CASI has delivered a wide range of research and educational events involving many local, national, and international farmer and research experts and in 2007 twelve California CASI members participated in a four-day tour of conservation agriculture sites in Nebraska, South Dakota and Wyoming that included farm and research facility demonstrations of no-till and strip-till planting and high residue management systems. These events have led to greater overall awareness of tillage system options as evidenced by increased farmer inquiries, media attention, and conservation agriculture equipment introductions in the CV.

3. Weak points needing attention

For each of the specific California cropping systems that are now beginning to use conservation agriculture principles, ongoing problem-solving is needed to make the systems more reliable and more widely used. In recent years, glyphosate-resistant (GR) weed populations have caused major challenges to the sustainability of conservation tillage cropping systems in many parts of the U.S. (Price et al., 2011). Such scenarios have not emerged in California's conservation agriculture systems as most herbicide-resistant weed populations in the state have been reported from orchards, vineyards, and rice cropping systems (Hanson et al., 2014). Nevertheless, improved and sustainable strategies need to be developed for weed management before the onset of such problems in California's conservation agriculture systems. The conservation agriculture dairy silage production sector is particularly at risk of herbicide resistance due to the availability of herbicide-tolerant corn varieties and the associated risks to over-rely on limited management options. Likewise, weed and salt management in subsurface drip tomato-dominated rotations that arise because of the limited soil wetting patterns of drip systems pose challenges to sustained CA management if preventive measures for herbicide and salt build-up in the soil in minimum tillage, bed-preserving systems are not developed and used.

Farmer experience with CA silage corn has also shown the following areas needing planning and early attention to be successful. These include coordination and GPS synchronization of strip-till and seeding equipment to avoid mis-alignment of these two operations. Experienced CA corn silage farmers also stress the need for early attention to both irrigation applications and weed management (Personal communication, T. Barcellos). Early surface irrigations may be required because surface water movement across fields that have only been partially tilled, as with strip-tillage, may be quicker and thus more frequent, but often times lower-volume irrigations may need to be applied. Likewise, because less tillage is done with CA systems, early-season weed control measures must be used so as to avoid weed infestations. A final potential hurdle identified in CA dairy silage systems in California is nutrient stratification from the lack of soil inversion tillage associated with no-tillage. Manganese deficiency, due to nutrient stratification in a strip-tillage corn crop, has been observed in Turlock, CA, but this problem hasn't been seen widely.

Table 2
Conservation tillage farmer and private sector innovators who have contributed to the development of new tillage system alternatives in California's Central Valley (2005–2014).

Year	Conservation tillage farmer innovator	Location
2005	Bob Prys	Riverdale, CA
2006	Tom Barcellos	Tipton, CA
2007	Jim Couto	Kerman, CA
2007	Tony Turkovich	Winters, CA
2008	Dino Giacomazzi	Hanford, CA
2009	Alan Sano	Firebaugh, CA
2009	Jesse Sanchez	Firebaugh, CA
2010	John Diener	Five Points, CA
2011	Fred Leavitt	Firebaugh, CA
2011	Steve Fortner	Firebaugh, CA
2012	Michael Crowell	Turlock, CA
2011	Fritz Durst	Woodland, CA
2012	Gary Martin	Firebaugh, CA
2013	Danny Ramos	Los Banos, CA
2014	Darrell and Trevor Cordova	Denair, CA
2015	Charlie Rominger	Winters, CA
Year	**Conservation tillage private sector innovators**	**Location**
2005	Al Ruozi	Bakersfield, CA
2010	Monte Bottens	Madera, CA
2010	Alan Wilcox	Walnut Grove, CA
2011	Juan Trujillo	Walnut Grove, CA
2011	Kevin McDonald	Modesto, CA

4. CA farmer innovator recognition program

Major transformations and innovations in agricultural production systems and technologies like CA, have had their early-phase pioneer farmer leaders and visionary champions (Dumanski et al., 2014a,b; Lindwall and Sonntag, 2010; Awada et al., 2014). In 2005, the CASI Workgroup established the Conservation Agriculture Farmer Innovator Award as a means for providing greater visibility to CA pioneers in California. The criteria for this award are demonstrated innovation and leadership in the development, refinement and use of conservation agriculture systems within California cropping systems. Nominations are received and reviewed by a Workgroup panel and recipients are announced

Photo 7. No-till center pivot-irrigated corn being seeded into winter forage mixture at the farm of Darrell and Trevor Cordova, Denair, CA, 2014, (Photo: J.Mitchell).

in CASI's annual conference. Since 2005, seventeen Central Valley farmers have been recognized as recipients of this award (Table 2). These farmers span a variety of cropping systems and regions from dryland no-till systems in Yolo County, to strip-till and no-till dairy silage production in Turlock and Hanford, to tomatoes and cotton in the central CV. In addition, four CA equipment entrepreneurs and a private sector consultant have also been recognized. These innovators visualized new paradigms and put in tedious and quite taxing development trial-and-error efforts that led to new systems. As a group, these farmer champions tend to be tenacious but calculating risk-takers who understand the complexity and challenges involved in making large-scale changes in existing production systems, but who also recognize the need to improve what they are doing (Lindwall and Sonntag, 2010; Awada et al., 2014; Bellotti and Rochecouste, 2014). Another remarkable characteristic of this entire group of innovators is their uncommon willingness to share their learning with others. CASI's 2014 Innovator Award recipients, Darrell and Trevor Cordova, of Denair, CA epitomize this attribute of generosity and openness. From their first attempts at conservation tillage for their edible dry beans/small grain rotation back in 2003, this father–son team has persevered through a variety of learning challenges on their CV farm's undulating hills to now successfully manage sustained no-till dairy silage corn and winter forage mixes irrigated with a 60.7 ha center pivot (Photo 7). They brought together a staggering array of private sector, NRCS and university advisors to help them with various aspects of their system and have achieved successful CA.

5. Conclusions

Where major changes in tillage systems have occurred, farmer experience with tillage innovation in California has been diverse and stems from a complex set of motivating factors (Awada et al., 2014; Bellotti and Rochecouste, 2014). While this review has been primarily to chronicle major trends in tillage management systems that have operated in California's Central Valley for the past 80 years as well as important introductions of new technologies and approaches, it is also important to consider the underlying factors that have enabled these transformations to occur.

Farmers who have changed their tillage practices in major ways, "felt a need to change" (Awada et al., 2014; Bellotti and Rochecouste, 2014). The long and gradual increase in agricultural production costs that began in the early 1980s and that continues today, along with farm labor shortages that have occurred have contributed to this perceived need for change in how things are done.

Secondly, a need to avoid further environmental regulations imposed during this time or from a recognition that benefits from combining production and environmental protection goals with lower input and labor-requiring practices, yields a shift from an exclusively production focus by some to a broader sustainability emphasis during this period that has been important in the increased adoption of new tillage systems in the Central Valley. Several of the CA farmer innovators who have been acknowledged for their tillage system innovations recognize, for instance, the importance of soil care along with their fundamental need to cut production costs whenever they can.

A third contribution to the transformations in tillage management documented here is the undeniable role of external influences on farmer innovations in the Central Valley. Farmers now are exposed to new ideas and technologies not only via the traditional extension education activities like CASI, but also through vast online resources. The role of these external influences that have included farmers, researchers, and private sector experts from literally all over the world, has been considerable during the past twenty or so years. No-till dryland Central Valley farmers, for example, learned directly from experienced no-till farmers in Washington. Several Central Valley strip-till and no-till farmers have also learned from information sources outside the region and have actually travelled to other regions to see what is possible under different conditions. The role of global farmer-to-farmer communication cannot be underestimated for its impact on conservation agriculture adoption.

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