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UC PEER REVIEWED

Publication 8331 / September 2008

Tillage and Crop Management Effects on Air, Water, and Soil Quality in California

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Conservation tillage (CT) has become an important management tool in production systems throughout the world. The term “conservation tillage” has been defined in various ways over the past 70 years, depending on the region in which it has been practiced. The USDA Natural Resources Conservation Service (formerly the Soil Conservation Service) defines CT as maintaining a minimum of 30 percent soil cover with crop residues after planting. Other definitions have arisen for special circumstances, such as 1,120 kg/ha^{-1} of flat, small-grain residue equivalents on the soil surface in areas with wind erosion potential (CTIC 2002; Lyon et al. 2004). In Australia, CT is the reduction of tillage operations but not necessarily the preservation stubble or residues, due to the difficulty of establishing crops in high-stubble loads given slow residue breakdown during dry summers (Lyon et al. 2004). In California, CT is considered to be the reduction in equipment passes in the field by 40 percent or a crop residue cover of 30 percent (Mitchell et al. 2007). The use of winter cover crops (CC) in low-residue tomato systems is an example of maintaining greater than 30 percent soil cover.

Well-documented benefits of CT production include reduced soil loss due to water and wind erosion; increased water infiltration and soil water storage; reduced labor, fuel and equipment use; improved soil tilth; increased cropping intensity; increased soil organic matter; and improved water and air quality (McLaughlin and Mineau 1995).

The collective advantages of CT correspond to widespread adoption. It has been estimated that in 2001–2002, 72 million hectares globally were under no-till, a form of CT in which no soil disturbance occurs from the harvest of one crop to the planting of the next (Derpsch and Benites 2003). This estimate includes about 50 percent of the cropland in Brazil and Argentina, 45 percent in Australia, and 20 percent in the United States.

Current estimates of CT adoption in California are far lower: about 2 percent in 2004, up from 0.5 percent in 2002 (UC Conservation Tillage Workgroup Survey 2006). In California, an adaptable model of CT has emerged across a broad range of crop production systems that minimizes or eliminates primary tillage operations of disking, plowing, ripping, and chiseling, and that manages residues in ways to enable efficient and successful planting, pest management, and harvesting. Despite the complexities (crop diversity and intensive inputs of fertilizer and irrigation) typical of California production systems, “classic” forms of CT that are common elsewhere (no-till and strip-till) are being implemented. As with CT, the use of CC to improve soil and reduce runoff has not seen widespread adoption. While these production alternatives are relatively new to California, there is a growing body of information related to their likely impacts on air, water, and soil quality and on resource conservation. This publication compiles information from these studies and projections.

CAPTURING AND MITIGATING TRACE GAS EMISSIONS FROM CALIFORNIA SOILS

Soil is a major reservoir for carbon (C) and nitrogen (N) in the terrestrial environment. Soil carbon accounts for two-thirds of the total terrestrial carbon budget, twice that held in the vegetation or in the atmosphere (fig. 1). Including wetlands markedly increases the soil C inventory. Carbon is stored in soils primarily in the form of humic substances bound to minerals that are resistant to decomposition, although a significant fraction of soil carbon is in various states of decomposition. Tillage is thought to expose humic substances to decomposers through disruption of soil aggregate structures (Six et al. 2000, 2002).

Crop rotations with little diversity reduce soil carbon by changing the quality and quantity of plant residue input and decomposer diversity (Horwath 2006). Disturbance of soil through tillage and low-diversity cropping affects the smaller nonmineral bound soil fraction, or the light fraction, to a much greater extent than it affects humic substances. The light fraction, composed of plant residues in varying stages of decomposition, is a significant source of

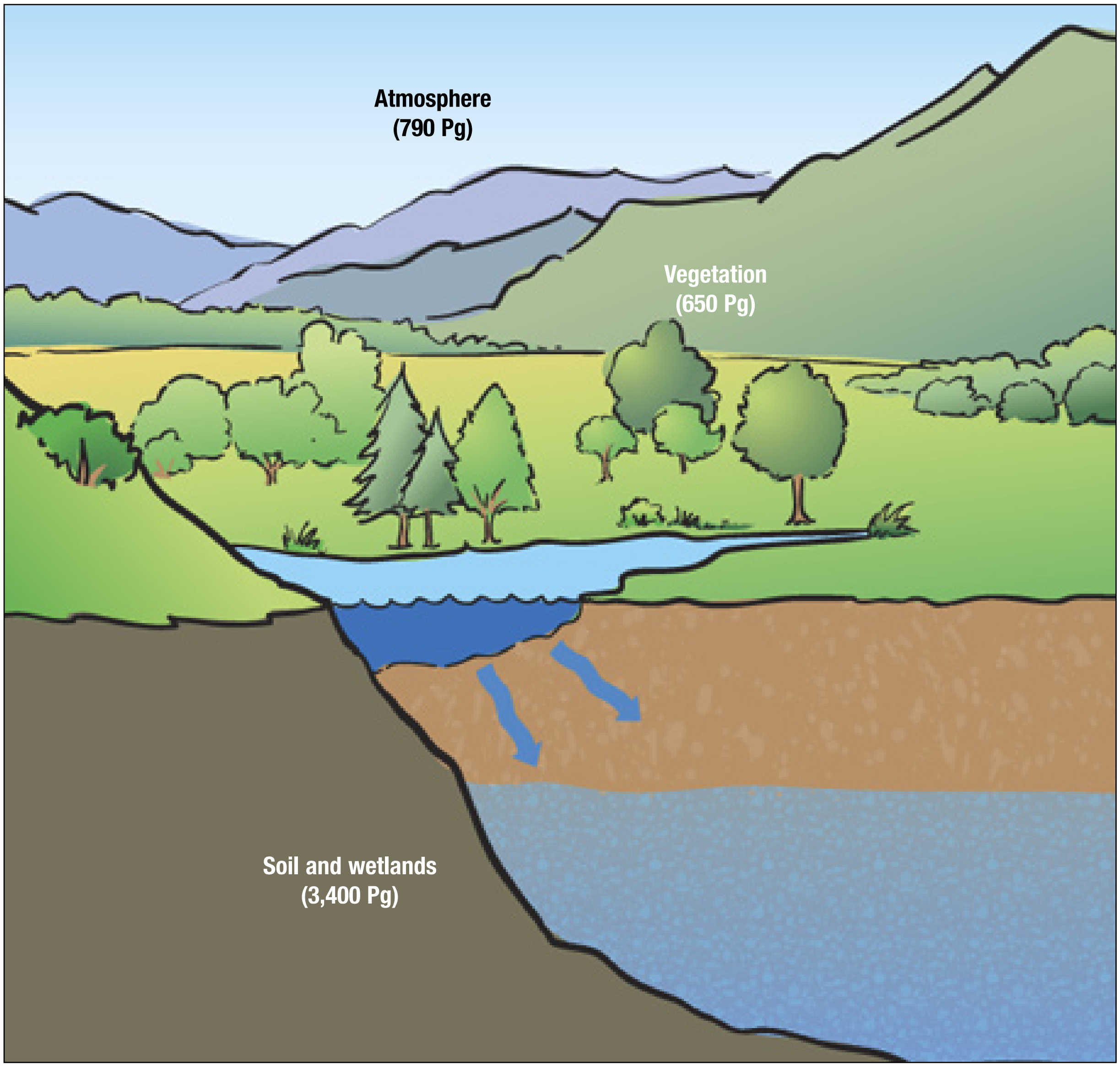

Figure 1. Soil and wetlands store over twice as much carbon than do vegetation and the atmosphere (1 petagram [Pg]= 10^{15}g = 10^{9}tons).

available nutrients (Seiter and Horwath 2004). The preferential loss of the light fraction can seriously affect the long-term productivity of the soil.

Fertilization combined with mineralization of soil nitrogen can contribute to increased emissions of trace gases such as nitrous oxide (N_2O) and oxides of nitrogen (NO_x). Significant emissions of nitrous oxide have been attributed to the use of nitrogen fertilizers; these account for greater than 50 percent of total emission from all sources (EPA 2006). The release of nitrous oxide, the most potent greenhouse gas, contributes to global climate change in the same manner as emissions from industrial sources. Therefore, management of soils can have profound influence on the sources and sinks for greenhouse gases.

CARBON MANAGEMENT IN CALIFORNIA SOILS

Agriculture, excluding pasture land, accounts for nearly one-third (28%) of the land use in California. Intensive irrigated agriculture, which is about one-third of the California total, represents the best opportunity for soil carbon management. A major difference between California agriculture and that in other areas of the world is the tremendous crop diversity and the ways in which agricultural land is used (fig. 2). Irrigation and fertilization have contributed to maintaining the phenomenal productivity of California agriculture (NASS 2005). Dramatic increases in tillage have been associated with special crop needs and furrow irrigation techniques (DeClerck and Singer 2003). For example, soil carbon has generally increased over the last 60 years on California agricultural land, presumably because productivity was greater than that of the native plant community, and because of changing climatic conditions (fig. 3). However, this comparison of soils is done without correction for changes in bulk density, which is necessary to determine the mass of soil carbon. Estimating soil carbon based on changes in concentration (%) does not indicate changes in total mass. Consequently, it is difficult to conclusively state that crop productivity and irrigation have led to increases in soil carbon.

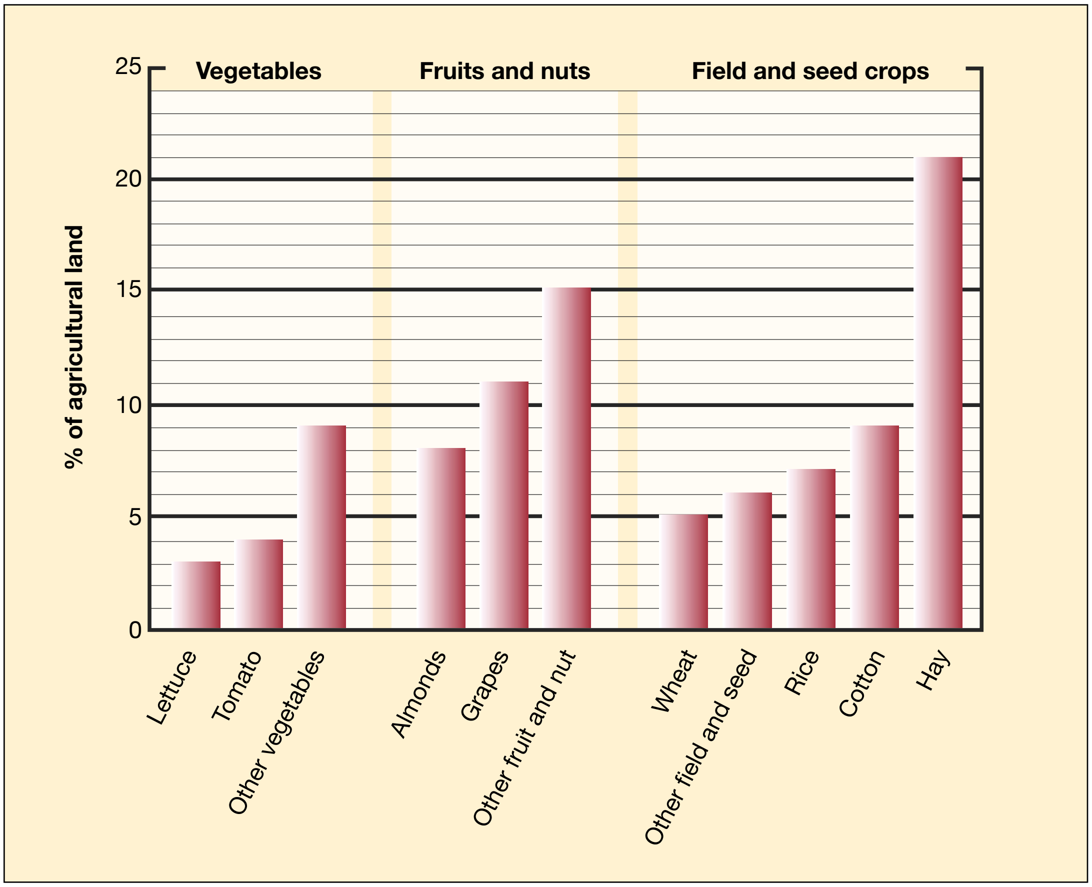

Figure 2. Amount (%) of crops in California in irrigated agriculture. *Source:* CDFA 2006.

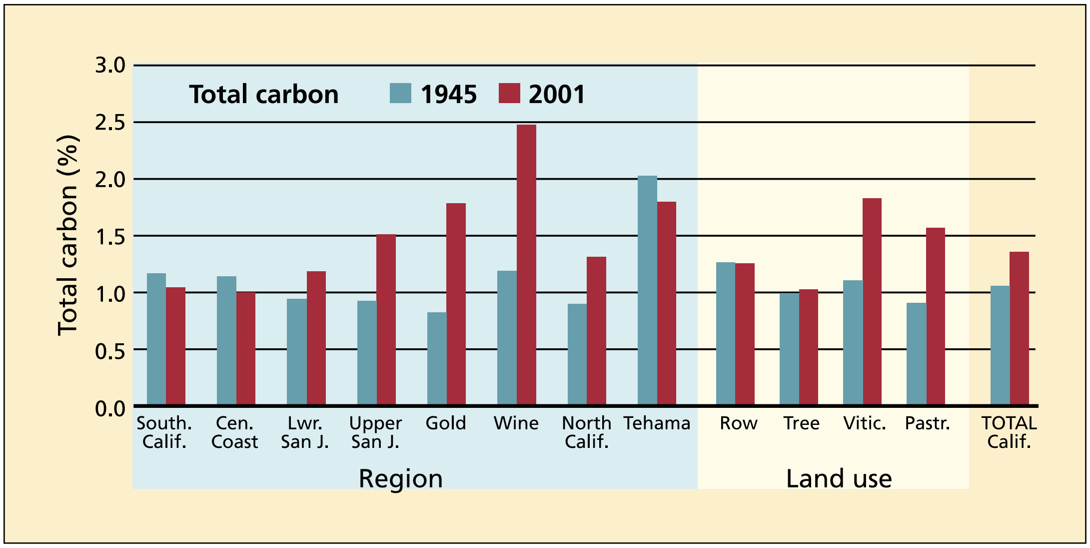

Figure 3. Soil carbon over the last 60 years by region and land use. *Source:* DeClerck and Singer 2003.

The key question remaining is to determine the set of management practices that will provide broadly applicable results for diverse land management strategies for California agriculture to reduce carbon and nitrogen loss to the atmosphere and from soil.

California soils are relatively carbon-poor in comparison to other temperate soils as a result of intensive management, residue-poor crop rotations, climate, and parent material. Climate is the critical factor affecting soil carbon through its effect on increasing decomposer activity. California's warm temperatures and efficient irrigation practices make an ideal environment for decomposers. For this reason, California agriculture soils contain on average about 1 percent soil carbon, compared with 2 to 4 percent in soils where winter temperatures reduce decomposer activity. However, because of this ability of soils to hold more carbon, there may be a greater potential for increasing total carbon storage in California agriculture soils. Potential management practices to increase soil carbon include CC, CT, changes in irrigation techniques, and diversified crop rotations that are managed for high-residue return.

WINTER COVER CROPS

Recent research by University of California, Davis, researchers quantifying the effects of management techniques on soil organic carbon showed a 36 percent increase in carbon over 12 years by changing from conventional agriculture to CC practices and manure applications (Horwath et al. 2002). The increase in soil carbon occurred despite an increase in tillage associated with these practices, indicating that increased carbon inputs from manure and CC are essential to maintaining and increasing soil carbon. The use of CC alone increased soil carbon by 20 percent compared with winter fallow systems. However, implementing CC as green manures in the intensively managed agricultural systems of California may delay field entry times following winter rains, necessitate reassessment of fertilizer nitrogen application rates, require additional irrigation to establish, and increase soil preparation and tillage. In addition, late CC incorporation may produce allelopathic effects impacting crop establishment (Seiter and Horwath 2004). For these reasons, the implementation of CC in California has been slow.

The increase in soil carbon and nitrogen from CC has many potential benefits that overshadow negative agronomic management aspects, including reduced winter runoff, increased soil fertility, potentially less nitrogen-containing trace gas emissions, and less nitrogen leaching. Poudel et al. (2001) found that winter CC can dramatically reduce the loss of fertilizer nitrogen, primarily as a result of increased soil carbon storage. However, because research on CC in California is limited, more research is needed to determine the effects of CC on trace gas emissions, especially nitrous oxide. Additional research is needed on CC types, especially mixtures (legume versus cereal), water requirements, and the effect of CC on soil fertility in California.

CONSERVATION TILLAGE

Tillage plays an important role in the management of soil nutrients through the incorporation of plant residues, seedbed preparation, pathogen incidence, and weed control. The type, frequency, and intensity of tillage determine the degree to which decomposition and mineralization processes occur. No-tilled soil can contain 20 to 43 percent more total nitrogen than conventionally tilled soil in the 0 to 5 centimeter soil depth (Gallaher and Ferrer 1987). To sequester the additional nitrogen, no-till soils tend to increase soil carbon in the upper few inches of soil. The increased shallow-soil nitrogen can increase nitrogen mineralization capacity compared with tilled soil (Seiter and Horwath 2004). However, when examining the 0- to 30-centimeter soil depth (and deeper), the differences in carbon and nitrogen content and nitrogen mineralization between no-till and conventional tillage are no longer apparent (Veenstra et al. 2007; Six et al. 2004).

In California, no-till management is beginning to be used in certain cropping contexts, but it is not currently a widespread practice. Reduced tillage, or CT, has shown promise in a variety of cropping systems and rotations, including those containing specialty crops such as tomatoes and melons (Mitchell et al. 2007). The primary reason for the low adoption of CT in California is the difficulty in determining the methods and technologies to introduce CT into California's intensively managed and irrigated cropping systems. One primary hurdle for adoption is that CT leaves crop residues on the soil surface, where they interfere with furrow irrigation practices. Other reasons include reassessment of fertilizer application rates, soil compaction, unfavorable seed germination environments (allelopathy and reduced soil temperature from the crop residue "mulch effect"), soil crust formation, and shallow soil salt accumulation. In the oldest (>5 years old) CT research plots in California, no increases were seen in total soil carbon in the surface 0 to 30 centimeters of soil; however, a redistribution of carbon and nitrogen was seen from deeper soil into the top 0 to 5 centimeters of soil under CT compared with standard tillage (Veenstra et al. 2006). Similar to other long-term studies with winter CC, a significant a increase in soil carbon and nitrogen was seen (Veenstra et al. 2007).

The effect of CT on nitrogen-containing trace gases has received little attention. Research on no-till soils generally shows an initial increase in nitrogen-containing trace emissions. This increase has been attributed to increases in soil bulk density—the weight of soil (in grams) per cubic centimeter—under no-till (Six et al. 2004). The research suggests that reducing nitrogen-containing trace gas emissions may take up to 20 years of continuous no-till management. Reduced diesel use under CT could potentially mitigate emissions of carbon dioxide and oxides of nitrogen in California agriculture. The impact of CT on trace gas emissions in California remains unclear and requires additional research.

CROP DIVERSITY

Although crop rotations are similar to amendment strategies such as CC and organic waste amendments, they are generally less effective at increasing soil organic matter in the short term (Seiter and Horwath 2004). The main reason for this is that crop rotations may decrease carbon input to soil, depending on the residue production of selected crops. Horwath et al. (2002) found that a 4-year rotation of corn, tomato, wheat, and safflower under conventional tillage had a more positive effect on soil carbon than a two-crop rotation of tomato and wheat. The effect was less than a 5 percent increase in soil carbon, substantially less than applying manure or growing a winter CC. Carefully planned rotations containing a variety of crops can maintain or enlarge active soil carbon pools to provide a steady supply of available nutrients for each crop in the rotation. Diversified crop rotations can also reduce weed and pest incidence (Seiter and Horwath 2004). However, many growers are often limited by the types of crops that can be grown in rotation because of soil types, climatic limitations, and economics. In addition, diversified crop rotations may present an array of problems for implementing CT practices in California. Each crop has specific soil preparation requirements (soil temperature and allelopathic response, for example), cultivation practices, and irrigation needs that create challenges for the universal adoption of CT in California.

IRRIGATION

One of the main obstacles to implementing CT is furrow irrigation—the most common irrigation practice in California. Crop residues that build up under CT can block and impede water movement in furrows. In addition, soil beds begin to slump

into the furrows with less tillage maintenance, decreasing the depth of the furrow and causing water to potentially flow over the beds. For this reason, under furrow irrigation practices, displacing crop residues and maintaining furrow geometry using tillage is seen as an impediment to the adoption of CT and CC practices. Moreover, the increased need for herbicides to control weeds in CT under furrow irrigation can lead to offsite transport of herbicides. Changes from current furrow irrigation practices to subsurface drip irrigation (SDI) or low-pressure overhead sprinklers can potentially solve many of the problems associated with CT adoption in California. With SDI, crop residues are no longer an impediment to delivering irrigation water or maintaining soil beds. The spatially delimited delivery of water in the SDI system also reduces weed growth and crop pathogens by maintaining a nearly dry soil surface during the growing season. Thus, the use of SDI can resolve problems of adopting CT by eliminating issues with cover crop trash in furrows and by reducing pesticide use. In a preliminary unpublished study, SDI reduced weed incidence more than 95 percent compared with furrow irrigation. The effective implementation of SDI requires precision farming practices using global positioning technology to locate crops over existing SDI lines. Preliminary unpublished research suggests that SDI significantly reduces nitrous oxide emission compared with furrow irrigation. More research is required to determine SDI effects on trace gases emissions.

AIR QUALITY IMPROVEMENT

An additional potential benefit of CT systems is lower dust or particulate matter emissions. The U.S. Environmental Protection Agency (EPA) has designated the San Joaquin Valley as a serious nonattainment area for PM10, particulate matter with an aerodynamic diameter less than 10 micrometers (µm). PM10 is a public concern because it can bypass the body's respiratory defense mechanisms and has been linked to a variety of cardiac and lung diseases. Air quality violations often occur during periods of intense tillage activity, with row crop agriculture being pinpointed as a major contributor of PM10. Conservation tillage has been shown to effectively reduce erosion and dust production in the Columbia Plateau by increasing surface residue and roughness (Stetler and Saxton 1996).

Dust production may be reduced by CT because it limits the number of passes through a field and improves key soil properties such as water-holding capacity and aggregate stability. Baker et al. (2005) evaluated four management systems to assess impacts on dust production for a cotton-tomato rotation in Five Points, CA: standard tillage with (ST-CC) and without (ST-NO) cover crop, and conservation tillage with (CT-CC) and without (CT-NO) cover crop. Gravimetric analysis of total dust (TD, i.e., <100 µm aerodynamic diameter) and respirable dust (RD, i.e., 4 µm aerodynamic diameter) collected in the plume generated by field implements showed that dust concentrations for CT-NO were about one-third less than with ST-NO for both cumulative TD and RD measured throughout the 2-year rotation, primarily due to fewer in-field operations (Baker et al. 2005). CT-CC produced about two-thirds the TD and three-fourths the RD of ST-CC. This study demonstrated that reduced dust is due largely to a reduction in the number of field operations.

In a follow-up, larger-scale study, Mitchell et al. (2005) conducted a 2-year comparison of CT and ST in dairy forage production to determine the extent to which CT might reduce PM10. Vertical profiling methodologies and EPA sampling protocols were employed to determine PM10 emission factors for both systems. Test results showed that CT reduced PM10 emissions by 64 to 97 percent in spring 2004 and by 53 to 88 percent in spring 2005. Again, PM10 reductions were mainly due to the fewer number of tillage operations in CT (from 0 to 1 operations to 3 to 6 in ST) and also because of the higher soil moistures at which CT operations can be performed.

In sum, these recent finding indicate considerable potential for CT to reduce dust emissions from farming systems. Additional work is now underway in the San Joaquin Valley to refine CT approaches that consistently reduce tillage passes and sustain productivity.

OPPORTUNITIES FOR CALIFORNIA AGRICULTURE

Conservation tillage production systems can significantly transform major sectors of California agriculture in the coming years. In their many and varied forms, CT systems reduce traditional soil preparation operations such as plowing, disking, bed maintenance, and ripping. Combined with the implementation of CC these new management

approaches can address issues related to agricultural runoff and greenhouse gas mitigation. Mitigation of greenhouse gas emissions and PM10 under CT and CC provides potential economic opportunities to the diverse range of farmers in California. We have shown evidence that CT reduces fuel use, production costs, dust, and winter water runoff. However, there remain many unanswered questions about the extent to which CT will become an important management tool for sustainable agricultural production in California. Nationally, 54 percent of farms in the United States generate less than $10,000 in sales on an annual basis (NASS 2005), making it difficult for low-income farmers to invest in machinery to facilitate CT. In California, half of farms fall into this economic class, with 29 percent generating sales from $10,000 to $100,000 annually. Financial credits for greenhouse gas mitigation through the use of CC or mitigation of carbon dioxide emissions through reduced diesel consumption under CT could benefit a significant portion of the farm population in California. While estimates of the use of CT in California are currently low, projections by UC's Conservation Tillage Workgroup indicate a largely unexplored potential for CT (Mitchell et al. 2007). Adoption of CT in California requires long-term assessment of its effects on soil properties, particularly soil compaction and salt accumulation at the surface of the soil (in the Midwest, the freezing and thawing of soils reduces the impact of soil compaction in no-till systems). Additional long-term studies by region and cropping system are required to confirm the benefits of adopting CT in California.

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Publication 8331

ISBN-13: 978-1-60107-578-9

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pr-9/08-SB/RW