Title of grant or project: **Optimizing water and nitrogen use efficient tillage and legume cover crop systems for California tomato and cotton production**

Principal Investigator: Jeffrey Peter Mitchell

Timeframe: October 2012 – October 2016

Grant Number: NRCS# 69-3A75-12-249, UCD# 201222849

Date of Submission: September 18, 2016

Deliverables:

This project has adapted and extended proven conservation tillage and cover crop practices using innovative technology transfer approaches to increase producer knowledge and encourage adoption. The following products were identified as deliverables from the initial objectives of the project:

Objective 1 *Soil quality training program*
  a. 2 annual field workshops (spring and fall) for producers and consultants
  b. Fall project-related conference at 4 SJV locations
  c. An annual NRCS Tech Note
  d. Printed observations and data from legume CC screening trials
  e. A framework for improved N and water use efficient tillage and CC management
  f. 4 popular press news releases annually
  g. 3 peer-reviewed journal publications
  h. Survey questionnaire data related to impacts of producer training program

Objective 2 *Soil quality and microbiological properties monitoring*
  a. Characterization of practical, functional differences in soil quality and microbiology that may result from CT and CC management in the SJV

Objective 3 *N budgets and use efficiency monitoring*
  a. Quantitative estimates related to legume cover crop N availability and the potential for farmers to use less N fertilizer

In addition, the following products will be delivered, as required:

  a. Semi-annual and final reports
  b. Supplemental narratives to explain and support payment requests
  c. Performance items specific to the project that indicate progress
  d. New technology and innovative approach fact sheet
  e. Participation in at least one NRCS CIG Showcase or comparable NRCS event during the period of the grant

Some adjustment in the actual implemented priorities of this work has occurred as discussed later in this final report.

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Executive Summary

The project, Optimizing water and nitrogen use efficient tillage and legume cover crop systems for California tomato and cotton production, was an initially three-year effort that was begun in the fall of 2012, and later granted a 15-month no-cost extension in 2015 through the fall of 2016.

Major accomplishments of this CIG project include:

a. Extensive extension education training program initiated related to the project's investigations of soil health impacts of cover cropping and no-tillage in California's San Joaquin Valley (SJV),
b. cost/benefit determinations of no-tillage and cover cropping practices in the SJV where they have previously not been evaluated,
c. demonstrations of the feasibility of using no-tillage and cover crop practices for sustaining crop yields at levels matching yields with conventional practices,
d. characterizations of changes in a number of soil properties and functions that result from the no-tillage and cover crop practices that have never been evaluated in the SJV, and
e. the project's spawning of the California Farm Demonstration Network which is a growing effort that is aimed at connecting people, developing information, and providing performance evaluations of conservation agriculture systems in California.

We wish to emphasize that we deliberately include quite significant detail in this final report because we are actually very proud of the work that this project has accomplished and because we wish it to be taken into account by NRCS as being, we believe, a rather remarkable CIG project in terms of overall impact.

Introduction

This final report to the USDA NRCS provides a comprehensive summary of our 2012 Conservation Innovation Grant project, Optimizing water and nitrogen use efficient tillage and legume cover crop systems for California tomato and cotton production," (NRCS #69-3A75-12-249, UCD# 201222849). Work conducted for this project was performed at the University of California's West Side Research and Extension Center in Five Points, CA and also at a variety of training and presentation sites in California and beyond. Funding for this project was provided by USDA NRCS under the above-referenced agreement.

Background

The goals of this project have been to 1) establish a comprehensive soil quality training program in the San Joaquin Valley (SJV), 2) characterize soil quality and soil microbiological properties of no-tillage cover cropped soils compared to conventional tillage soils without cover crops in a long-term cropping systems study in the SJV, and 3) to investigate soil carbon and nitrogen characteristics of the soils in this study as a basis for then widely disseminating locally-derived information from the work.

This CIG project has been implemented by the team that was originally identified in our 2012 proposal that included colleagues at the University of California, Davis, the UC's Cooperative Extension Service, local farmers, and USDA NRCS, private sector, and other agency partners.

The project has been unusually successful in meeting its core objectives and has greatly exceeded its original expectations by the quantity, quality, and depth of educational and impact outcomes that it has achieved. It now provides a unique research and extension education context that has quantified impacts of long-term no-tillage and cover crop management on productivity, economics, and soil function within the historically productive SJV where such practices are not at all widely used.

This project has provided the core information basis for over 150 educational presentations on soil health and alternative production systems to over 1000 beneficiaries. It furnished the information and experience basis for the California Farm Demonstration Network which has been formed with a small State CIG, and it has generated four peer-reviewed scientific papers, with an additional four manuscripts now submitted for consideration for publication. We go to the trouble in this final report to NRCS of laying out in some detail the range of accomplishments of this CIG project.

Review of methods

This project has evaluated, generated and extended information on the innovative practices of no-tillage and cover cropping, - which are by no means novel for some regions of the US, but they are new and thus, innovative for the SJV region of California.

For purposes of this final report to NRCS and so to make the information contained in this report as clear and easy to follow as possible, we present our accomplishments and outcomes according to the three initial objectives of the work. We note up front, however, a few ways in which aspects of the work shifted or were slightly refocused during the course of the project in order to emphasize what we believed to be the best set of possible outcomes with respect to information generation and opportunities for scaling up the adoption of improved performance systems. For instance, while the project was originally conceived as a tomato-cotton rotation-based effort, we realized during the course of our annual project planning sessions that we could better achieve our overall goal of evaluating actual conservation agriculture systems if we actually employed an important principle of conservation agriculture, - diversity, in the experimental and demonstration work that we were evaluating. Thus, in the past three seasons, we have shifted from the cotton-tomato rotation scheme we used from the project's inception in 1998, to a more diverse rotation that now has included garbanzos and sorghum, - two more water use efficient entries that also made more sense in light of the State's recent sustained drought. During the course of this work, we also ended up emphasizing more of the overall soil health or soil function aspects of the project than the soil nitrogen aspects per se. We think that this has been a useful and productive slight shift in our overall emphasis that has yielded many good outcomes.

In the remainder of this "Review of methods" section, we provide documentation of how each of our three objectives has been achieved by providing specific evidence and documentation of progress. In some cases, we provide excerpted text from publications that are either published, in press, in review, or in revision. We identify sections that have not yet been published and ask that these not be treated by NRCS as peer-reviewed material. We would like to point out in this final report that this CIG project has yielded exceptionally valuable and extensive outcomes that now provide considerable information about how soils change in the SJV under no-tillage and cover crop management. This now locally-derived information is uniquely valuable to the soil health campaign of NRCS here in California and it has already and will continue to provide solid, regionally-relevant findings for our region that had not been available before this work was done. We hope that NRCS recognizes the sheer amount and quality of work that this CIG project has accomplished.

1) Objective 1 Soil quality training program

Based on the core long-term experimental work that we have conducted in Five Points, CA since 1999, we used information that has been compiled in this work as the basis for a training program on soil health that has involved actual content presentations at over 150 events to over 1,000 adult recipients and over 1,500 K – 12 children. Each of the following individual presentations contained information and outcomes that resulted directly from this CIG Project study in the 8-acre experimental field where the work was conducted.

1. November 18, 2012. California Tomato Research Institute. 4 pages. Precision tomato production systems for increased competitiveness and resource use efficiency. Report on work related to this CIG Project.

2. December 6, 2012. Prepared and provided Powerpoint presentation for California Tomato Research Institute Annual Board Meeting, Davis, CA. Related to this CIG Project.
3. December 7, 2012. Prepared and provided Powerpoint presentation for 11th Annual Sustainable Ag Conference, Pest Management Conference, San Luis Obispo, CA. Related to this CIG Project.
4. January 13, 2013. Beyond conservation tillage: Merging technologies for greater efficiencies. American Society of Agronomy. California Chapter. 3-page article. Related to this CIG Project.
5. January 28, 2013. Using conservation tillage to reduce PM emissions. Tech Note 000 for USDA Natural Resources Conservation Service. Provided draft of Tech Note upon request of NRCS Johnnie Siliznoff. Related to this CIG Project. Report was enabled by work directly conducted and associated with this project.
6. January 29, 2013. Surface residues and no-tillage reduce soil water evaporation. UC DELIVERS. http://ucanr.edu/delivers/?impact=908&delivers=1&called_from_delivers=1 This work stemmed from this CIG Project. The primary photo that was used in this article and the California Agriculture Journal article in which the work appeared was from the experimental field where this CIG Project work was conducted.
7. February 5, 2013. Improving yield with continuous cropping systems. Invited presentation. Basin Fertilizer Grower Update 2013. Fall River Valley, CA. 100 participants. Presentation summarized this CIG Project work.
8. February 8, 2013. Beyond conservation tillage: Merging technologies for greater efficiencies. 2013 California Plant and Soil Conference. Keeping California Agriculture Proactive and Innovative. Marriott Convention Center, Visalia, CA. 50 participants.
9. February 12, 2013. Provided interactive display and boot on the Conservation Agriculture Systems Innovation Center. World Ag Expo, Tulare, CA.
10. February 13, 2013. Interactive display and informational booth on the Conservation Agriculture Systems Innovation Center. World Ag Expo, Tulare, CA.
11. February 14, 2013. Educational display and information booth on the Conservation Agriculture Systems Innovation Center. World Ag Expo, Tulare, CA.
12. February 21, 2103. Development of conservation agriculture systems in the Central Valley. Invited presentation for Progressive Farmers. Blythe, CA. 20 participants.
13. February 22, 2013. Diversified farming systems: A role in drought resilient agriculture. Invited presentation. UC Berkeley. Center for Diversified Farming Systems. 25 participants.
14. February 26, 2013. Radio Interview. Cover crop research in California. KALZ/KRZR PowerTalk Fresno/Visalia.
15. February 28, 2013. Soil water holding capacity. Oregon Soil Quality Network. McMenamin's Edgefield, OR. 4 presentations. 50 participants. Invited presentations for the Oregon Soil Quality Network.
16. March 1, 2013. Soil quality initiatives of California's Conservation Agriculture Systems Innovation Center: Motivation, goals, and adoption campaigns. Oregon Soil Quality Network, McMenimin's Edgefield, OR. Invited presentation. 100 participants.

17. March 5, 2013. Invited class lecture. AG115. California State University, Fresno. Does conservation agriculture have relevance in California? 15 students.

18. March 7, 2013. Invited class lecture. PLS100B. UC Davis. Crop plant growth and development. Crop rotation cycles. 20 participants.
19. March 8, 2013. CASI research goals and initiatives here at the WSREC. Presentation to staff of UC West Side Research and Extension Center, Five Points, CA. 10 participants.
20. April 18, 2013. Presentation on CASI to Rose Hayden-Smith. UC ANR Strategic Initiative Leader for Sustainable Agriculture. UCCE San Luis Obispo, CA.
21. April 11, 2013. Presentation on CASI to Ashley Boren and Ladi Asgill of Sustainable Conservation. San Francisco, CA.
22. May 3, 2013. Keynote speech. 2012. Leopold Conservation Award Ceremony for Dino Giacomazzi. Hanford, CA. 40 participants.
23. May 5, 2013. Provided slides and notes for Chris van Kessel on conservation tillage. PLS150 class at UC Davis.
24. May 3, 2013. Prepared and presented 15 poster displays for 2012 Leopold Conservation Award Ceremony for Dino Giacomazzi. Hanford, CA. 40 participants.
25. May 3, 2012. Received the Jeff Mitchell Award at 2012 Leopold Conservation Award Ceremony for Dino Giacomazzi, Hanford, CA 40 participants.
26. May 21, 2013. Hosted Henry He and other Chinese visitors at the UC West Side Research and Extension Center, Five Points, CA
27. June 2013. Presentation on CASI for Acting Dean Mary Delaney and Associate Dean Jan Hopmans. UC Davis College of Agriculture and Environmental Sciences. Davis, CA
28. July 9, 2013. Vegetable crops research update. Changes in soil properties with long-term cover cropping and conservation tillage. Public conference at the UC West Side Research and Extension Center, Five Points, CA.
29. June 27, 2013. Presentation on CASI to Agricultural Sustainability Institute. UC Davis. 20 participants.
30. June 28, 2013. Presentation on CASI to the University of California Division of Agriculture and Natural Resources. 20 participants.
31. June 25, 2013. Presentation on CASI to the California Cotton Ginners and Growers' Associations. Fresno, CA.
32. July 9, 2013. Presentation at the Vegetable Crops Research Update Meeting. Comparison of drip and overhead irrigation using minimum tillage. 30 participants.
33. July 10, 2013. Western Farm Press. Todd Fitchette. California cotton farm gives no-till a try. Provided interview information for Western Farm Press article.
34. July 30, 2013. Hosted Valmont Irrigation Company executives, Ray Batten, Jerry Gerdes, and Shane Shiplet. UC West Side Research and Extension Center, Five Points, CA. Invited presentation.
35. July 31, 2013. Invited field presentation. Long-term CT research in the San Joaquin Valley. NRI Project Introduction. Field presentation for ANP California Ag Solutions. 20 participants.

36. July 31, 2013. Invited indoor presentation. History and achievements in conservation agriculture in California. ANP, Advanced Nutritional Products, California Ag Solutions. 20 participants.
37. August 2, 2013. Invited tour group presentation to group of five Chinese Ministry of Agriculture and three California State University, Fresno guests. I provided a tour of two experimental conservation agriculture fields as well as a prepared Powerpoint presentation in Five Points, CA.
38. May 30, 2013. 2013 No-till cotton field tour. Firebaugh, CA and Five Points, CA. Organized and hosted public field day for 40 participants.
39. August 20, 2013. NRCS Hanford, CA. Soil Quality – What have we learned in California? Invited presentation and classroom teaching. 20 NRCS staff.
40. August 21, 2013. Provided technical information and experience for dairy strip-till tour of Madera and Merced counties. 30 participants.
41. August 22, 2013. Provided technical information and experience for dairy strip-till tour of Kings county. 30 participants.
42. September 11, 2013. Organized and conducted tour for out-of-state visitor, Dr. Suat Irmak, of the University of Nebraska for CASI Workgroup and host dinner.
43. September 12, 2013. Organized and led 200 participant Precision Irrigation and Conservation Agriculture Farm and Field Tour events, Five Points, CA.
44. September 11, 2013. Soil quality: Reduced disturbance management impacts on soil quality. Tour stop of Precision Irrigation and Conservation Agriculture Farm and Field Tour. 200 participants.
45. September 12, 2013. Led awards ceremony for CASI CT Farmer/Industry/Workgroup recognition. Precision Irrigation and Conservation Agriculture Farm and Field Tour.
46. September 18, 2013. 96.7 KZRZ Power Talk radio interview segment on Precision Irrigation and Conservation Agriculture Farm and Field Tour.
47. September 18, 2013. UC ANR Radio/Video blog posted on the CASI website based on the September 18, 2013 radio interview.
48. September 24, 2013. Valley Gold. National Public Television video shooting. Invited by the Fresno County Farm Bureau.
49. September 22, 2013. Provided information to Carol MacNeil, Cornell University Cooperative Extension for reduced tillage vegetable production conference.
50. October 30, 2013. Provided information for Ashley Boren, Sustainable Conservation, for her presentation to UC ANR Sustainability Advising Committee with UC President Janet Napolitano.
51. October 16 – 30, 2013. Hosted Dr. Partha Biswas, Indian Council of Agricultural Research, New Delhi, fo 1.5 weeks study visit of conservation agriculture. Organized training program and educational visit with 20 people.
52. October 26, 2013. Organized PLS110A San Joaquin Valley field trip for 30 UC Davis students to San Joaquin Valley farms and the UC West Side Research and Extension Center.
53. November 1, 2013. Written progress report to Valmont Industries on onion and wheat overhead irrigation project.

54. November 8, 2013. California Tomato Research Institute. Annual Report. Design and investigation of water use efficient and 'climate smart' risk management cropping systems for tomato in the Central Valley. 4 pages.

55. November 5, 2013. ASA/CSSA/SSSA Annual 2013 Meeting, Tampa, FL. Invited symposium presentation "Coupling technologies to improve crop water productivity in California's San Joaquin Valley. In Improving crop water productivity through innovative irrigation and dryland management. Water, Food, Energy and Innovation for a Sustainable World.

56. November 15, 2013. Invited training presentation for the California Association of Resource Conservation Districts Annual Meeting. Accelerating adoption of conservation agriculture systems in California's San Joaquin Valley. Napa, CA. 10 participants.

57. November 13, 013. Valley's Gold – Cotton. Channel 18. Valley PBS. Valley's Gold – A partnership between the California Federation of Farm Bureaus and Valley PBS. 5-minute invited field presentation and interview. http://valleypbs.org/valleysgold/?cat=1

58. December 5, 2013. California Tomato Research Institute. Evaluation of precision commercial tomato production systems. Oral presentation at the Annual Meetings. Davis, CA.

59. December 10 and 11, 2013. Hosted and provide tours for Brendon Rockey and Jay Fuhrer at UC Davis and Five Points, CA. Organized, convened and moderated workshops on soil quality. Together these events drew over 150 participants. Tours included CIG study site.

60. January 1, 2014. Provided article to the California Cotton Ginners and Growers' Association on Roger Isom hosting PLS110A class in Five Points, CA.

61. January 7, 2014. Provided slide sets to Jesse Sanchez, Firebaugh, CA, for his trip and presentation with Cornell University, NY.

62. January 11, 2014. Linking production with sustainability – The conservation agriculture revolution in California. Invited presentation at San Jacinto High School FFA and agriculture students and Scott Brothers Dairy Farm. 10 participants.

63. January 14, 2014. Thoughts for improving production efficiencies and soil health in San Joaquin Valley row crop rotations. Discussion with Myron Yamasaki, Tim Ustick, Dox Marchini, Bart Sanguinetti, Danny Ramos, Woody Thorp, and Brenna Aegerter. Invited presentation. Tracy, CA.

64. January 18, 2014. Additional ecosystem services can be found in no-till tomato and cotton farms. Press release out to >132 print media outlets and CASI Center electronic distribution system.

65. January 25, 2014. Linking production with sustainability. The conservation agriculture revolution in California. Invited presentation to Firebaugh High School students. Firebaugh, CA.

66. January 28 and 29, 2014. Accelerating adoption of no-till. Invited presentation at the 2014 Winter Conference of No-till on the Plains. >1400 farmer participants. I made four 50 minute presentations. Salina, KS.

67. January 30, 2014. Invited participant. “Agriculture’s Innovative Minds (AIM) Symposium. Salina, KS. In conjunction with the 2014 Winter Conference of No-till on the Plains.

68. February 6 – 7, 2014. High residue farming systems in California’s San Joaquin Valley. Invited presentation at the Western Irrigated High Residue Farming Systems Meeting in Salt Lake City, UT. 25 participants.

69. February 10, 2014. Controlled traffic, precision irrigation onion production evaluation. California Garlic and Onion Symposium. 2014. Agriculture Building Auditorium. UC Cooperative Extension, Tulare, CA. 100 participants.

70. February 12, 2014. ‘The case for no-till farming in the San Joaquin Valley. Invited presentation. ASABE American Society of Agricultural and Biological Engineers. California-Nevada Section 150 participants.

71. February 13, 2014. Precision irrigation + cover crops – tillage = A formula for farm sustainability. Invited presentation as part of UCCE’s 100th Celebration of Science and Service. World Ag Expo 2014. Tulare, CA. 25 participants.

72. February 14, 2014. “We did this so you wouldn’t have to.’ Invited presentation. Vegetable Crops Research Update. Fresno County. UCCE West Side Research and Extension Center. Five Points, CA. 40 participants.

73. February 17 – 19, 2014. National Cover Crop Conference. Invited and paid for representative at this national conference sponsored by the Sustainable Agriculture Research and Education Program of USDA and NRCS. Omaha, NE. I was the only representative chosen from California.

74. February 2014. ‘More ecosystem services found in no-till farms. P. 20. In Vegetables West Grower and PCA magazine. Vol. 18. No. 2. February 2014.

75. February 28, 2014. Presentation to J.G. Boswell Company for 9 managers and George Wurzel. CASI. Corcoran, CA.

76. March 4, 2014. Water-use-efficient tillage, residue and irrigation management. Invited 20-minute video production for UCCE Drought Insights Series. UC Davis.

77. March 5, 2014. Water-use-efficient tillage, residue and irrigation management. Invited presentation. Department of Water Resources. Sacramento, CA. 15 participants.

78. March 7, 2014. CASI Work Introduction to John Harris, William Bourdeau, and Steve Ozuna. Coalinga Junction, CA.

79. March 12, 2014. Water-use-efficient tillage, residue and irrigation. Invited presentation and Departmental Seminar. Department of Agricultural and Biological Engineering. UC Davis. 25 participants

80. March 10, 2014. Water-use-efficient tillage, residue and irrigation management. Field interview session. Todd Fitchette. Western Farm Press. Five Points, CA.

81. March 11, 2014. Radio interview with Don York, KMJ580. Water-use-efficiency. Aired on March 12 and 13, 2041.

82. March 18, 2014. ‘Taking a Stand.’ Invited NRCS Soil Quality Training Session. Santa Rosa, CA. 30 participants.

83. March 19, 2014. ‘Taking a Stand.’ Invited NRCS Soil Quality Training Session. Riverside, CA. 25 participants.

84. March 204. Radio Interview. KALZ/KRZR Power Radio Talk. Fresno/Visalia Power Talk 1360 and 1280. Clear Channel Media and Entertainment. Doug Cooper.

85. March 25, 2014. 2013 – 2014 SARE Report from the Field. Contributed photos and interview for Andy Zieminski. Communications Manager, SARE Outreach.

86. April 2, 2014. Hosted and arranged full-day tour and in-depth interview for Nathanael Johnson. Journalist with 'Grist.'

87. April 17, 2014. 'No-till farming's Johnny Appleseed in a grimy Prius.' Nathanael Johnson. Grist.org. http//grist.org/food/no-till-farming-johnny-appleseed-in-a-grimy-prius/

88. March 20, 2014. 'Taking a Stand.' Invited NRCS Soil Quailty Training Session. Salinas, CA. 30 participants.

89. May 8, 2014. UCCE 100th Anniversary. Booth display on soil quality. Garden of the Sun. Invited presentation for UCCE Fresno. Fresno, CA. 50 participants.

90. May 22, 2014. MS Exam Committee. Ai Sun. International Agriculture Development.

91. May 23, 2014. Presentation to 9 fourth grade classes on soil quality as part of the 2014 AgVenture Day. Tulare County Farm Bureau, International Agri-Center and UC Cooperative Extension. Roughly 700 participants.

92. May 26, 2014. Presentation and tour ourganized for 3 visitors from Peru at the UC West Side Research and Extension Center, Five Points, CA.

93. May 27, 2014. Soil care in alternative production production systems. Invited presentation at 2014 Spring Vegetable Crops Symposium. UC West Side Research and Extension Center. Five Points, CA. 30 participants.

94. May 31, 2014. Hosted/ organized a 3-stop San Joaquin Valley tour for Carol Shennan and her UC Santa Cruz agroecology class. Giacomazzi Dairy, T & D Willey Farms, and UC West Side Research and Extension Center, Five Points, CA.

95. June 4, 2014. Organized and hosted USDA NRCS – Mexico Tour group to the San Joaquin Valley. Foreign Agriculture Service Group. Darrell Cordova and Alan Wilcox.

96. May 30, 2014. Hosted two Brazilian visitors at Five Points, CA Conservation agriculture field tour.

97. June 9, 2014. Hosted Eric Kueneman and Judee Fisher, former FAO workers on conservation agriculture. Organized tour and presentations on conservation agriculture in California.

98. June 12, 2014. Hosted Renata Brillinger and Judith Redmond. Requested invitation and tour organization. Five Points, CA.

99. June 16, 2014. Hosted 20 guests from Afghanistan and UCD International Programs Office at the UC West Side Research and Extension Center, Five Points, CA. Requested organization of tour, presentation, and luncheon.

100. June 17, 2014. Department of Pesticide Regulation. Invited panelist on soil microbial amendments panel. How management options improve soil health. California Department of Food and Agriculture. 150 participants.

101. June 19, 2014. Organized soil health training for NRCS staff. Dennis Chessman, State Agronomist and Tom Hedt, State Resource Conservationist. UC West Side Research and Extension Center, Five Points, CA.

102. June 23, 2014. Development and expansion of conservation agriculture systems in California's Central Valley. J.P. Mitchell, R. Harben, Robert Roy, D. Munk, M. Bottens, B.

Gale, J. Diener, D. Giacomazzi, J. Warnert, A. Bossange, K. Knudson, A. Shrestha, and G. Sposito. Proceedings of the 6th World Congress on Conservation Agriculture. Manitoba, AL. Canada. June 22 – 26, 2014. Invited, paid-for oral presentation and proceedings article.

103. July 10, 2014. Equilibrium Capital, San Francisco. Provided phone interview information to venture capital firm regarding opportunities for carbon sequestration via no-till in California.

104. July 11, 2014. Phone interview for Todd Oppenheimer. Journalist. Los Angeles Times, San Francisco Chronicle and Sacramento Bee. 'Carbon Farming.' July 9, 2014 email reply also.

105. July 6, 2014. Charles H. Ferguson. Provided phone and email information to Charles H. Ferguson. Academy Award Winning film director for documentary film on climate change.

106. July 16, 2014 and August 26, 2014. More crop per drop. No-till farming combats drought. Olivia Maki. Provided interview input that was cited in the 'civileats.com blog. Phone interview for journalist about no-till. http://civileats.com/2014/08/26/more-crops-per-drop-no-till-farming-combats-drought/

107. July 17, 2014. Phone interview for private sector entrepreneur regarding individual overhead irrigation span variable frequency drive.

108. August 14, 2014. No-till organic vegetable production. Invited Sustainable / Organic Production in the South San Joaquin Valley. World Ag Expo. OFAC and Tulare/Kings Counties CAPCA. 200 participants.

109. August 25, 2014. Invited participant at Ukiah soil health group planning meeting. UCCE, NRCS, RCD. Hopland Research and Extension Center, Hopland, CA. 15 participants.

110. September 16, 2014. Hosted Nigel Corish, Nuffield Scholar, Australia. Conservation agriculture production field tour and farm visit.

111. September 16, 2014. Hosted Jon Johnston, Howard Herd, Tom Herd, Dan Schueler, and Rick Hanshew at UC West Side Research and Extension Center in Five Points, CA. Private sector pivot irrigation company representatives. Field tour and introduction to our pivot irrigation work.

112. September 22, 2014. MS exam committee, Katherine Grazer. Hort and Agronomy. University of California, Davis.

113. September 24, 2014. PhD exam committee. Shu Yu. Hort and Agronomy. University of California, Davis.

114. Sptember 26, 2014. Invited presentation on cover crops for the San Joaquin Valley. Bowles Farming, Los Banos, CA.

115. October 3, 2014. Invited class presentation. California State University, Fresno. Plant Science Department. Tour of field station at the West Side Research and Extension Center. Five Points, CA 20 participants.

116. November 4, 2014 ASA/CSSA/SSSA 2015 Annual Meeting. Cover crop biomass production and water use in California's San Joaquin Valley. Invited Symposium presentation. Cover crops and soil health: 1. Session No. 270. With A. Shrestha, T.C. Hsiao, and S. Irmak.

117. November 4, 2014 ASA/CSSA/SSSA 2015 Annual Meeting. Invited Special Session presentation. When water becomes more valuable than land: Insights from the California drought. Irrigation and crop management impacts and innovations associated with California's current drought. 100 participants.

118. November 6 and 7, 2014. Hosted Dr. Andrew Price, USDA ARS Soil Dynamics Laboratory, Auburn, AL Tour and coordinated presentations in Five Points and Davis, CA.

119. November 10, 2014. Water use efficient tillage and water management. Invited presentation to California State University, Fresno PS 270 class of Dr. Dave Gorahoo.

120. November 12, 2014. Invited soil health planning meeting contributor. UC Hopland Research and Extension Center, Hopland, CA.

121. November 13, 2014. Invited presentation on US Peace Corps experience. University of California, Davis. 20 participants.

122. November 18, 2014. Invited presentation on processing tomato production with pivot irrigation. Michael Boparai, Walnut Grove, CA.

123. December 9, 2014. Innovative conservation agriculture options for improving soil health. Invited presentation. UC Hopland Research and Extension Center, Hopland, CA. 100 participants.

124. December 10, 2014. Irrigated conservation agriculture in California. Invited presentation. Washington State University, Moses Lake, WA. Building soils for better crops. 2014 Conference. Big Bend Community College, ATEC Building.

125. December 11, 2014. Precision irrigation and conservation tillage: A plan for improving forage production systems. Invited presentation. UC California alfalfa and grain symposium. Long Beach Convention Center. Long Beach, CA. 75 participants.

126. December 16, 2014. Provided interview for James Giese on cover crops for Mexican farmer magazine.

127. January 13, 2015. Invited presentation. FARMS Leadership Workshop #4. UC Kearney Agricultural Research and Extension Center. Parlier, CA. "Caring for our soils: Why is it important?" Presentation and hands-on learning activities. 30 students from Laton, Chowchilla, Sanger, Coalinga, and Woodlake High Schools.

128. January 22, 2015. Invited presentation. Water use efficiency: Combining techniques to increase WUE. Soil Plant and Water Relations class. California State University, Fresno. Class of Dr. Sharon Benes. 10 participants.

129. January 27, 2015. Invited presentations. FARMS Leadership Workshop #5. "Caring for our soils: Why is it important?" Presentation and hands-on learning activities for three groups of students from local San Joaquin Valley high schools.

130. January 28, 2015. Invited keynote speech. Lundberg Family Farms. Winter meeting. Richvale, CA. 60 participants.

131. January 29, 2015. After 15 years of cover cropping and no-tillage, how have soil properties changed? Invited presentation. Northern SJV Processing Tomato Meeting. The CTGA 68th Annual Meeting of Members and Exhibits. Doubletree Hotel, Modesto, CA.

132. January 30, 2015. Invited presentation. Soil and water management in conservation agriculture vegetable production systems. General overview and future trend. Crop

rotations, conservation tillage, precision agriculture, soil management to improve enterprise profitability. Driscoll's Northern Region Production and Applied Research Meeting. Watsonville, CA. Driscoll's Cassin Ranch Conference Facility.

133. February 3, 2015. Invited keynote presentation. Conservation tillage cropping systems. 2015 New Mexico Chile Conference. Hotel Encanto de las Cruces. Las Cruces, NM. Invitation by Stephanie Walker, New Mexico State University. 200 participants.

134. February 10, 2015. CASI extension education presentations at the 2015 World Ag Expo, Tulare, CA.

135. February 11, 2015. CASI extension education presentations at the 2015 World Ag Expo, Tulare, CA.

136. February 12, 2015. CASI extension education presentations at the 2015 World Ag Expo, Tulare, CA.

137. February 26, 2015. Organized and spoke at "Innovative cover crop field day" in conjunction with Lucero Farms, El Nido, CA with Danny Ramos. 6-page handout and video produced following the event. https://www.youtube.com/watch?v=V00CaEqUbE8&feature=em-upload_owner

138. February 26, 2015. Hosted Greg Johnson, USDA NRCS and three guests from Colorado State University COMET Farm Model group in Five Points, CA. Greg Johnson is from the USDA NRCS Portland, OR Regional Technical Center.

139. March 3, 2015. Invited presentation. PLB100. Lecture to Plant Biology class of Kent Bradford, University of California, Davis. 20 participants.

140. March 5, 2015. Invited presentation. The importance of increasing soil carbon. 2015 Western Nutrient Management Conference. Grand Sierra Resort, Reno, NV. 140 participants.

141. March 6, 2015. Hosted Greg Wittenborn and Mike Dirker. Lockwood Seed and Grain Company, Chowchilla, CA at the University of California West Side Research and Extension Center, Five Points, CA.

142. March 10, 2015. Invited presentation. Cover crop water use. USDA NRCS Plant Material Center. 2015 Cover Crop Field Day. 50 participants.

143. March 11, 2015. Provided Powerpoint slide set to Dr. Lynn Epstein on CASI research and partnerships in California for her March 24, 2015 presentation on sustainable agriculture work with a Chinese delegation.

144. March 19, 2015. Invited presentation on center pivot irrigation to College of Agriculture and Environmental Sciences Real Estate Services Department. University of California, Davis. 5 participants.

145. March 25, 2015. Invited presentation. Soil and water management in California's San Joaquin Valley. 14 visitors from Uzbekistan. University of California West Side Research and Extension Center, Five Points, CA.

146. March 25, 2015. Invited presentation. Climate and Agriculture Partnerships. 2015. CalCAN Summit. University of California, Davis. Conference Center with Turlock, CA farmer, Michael Crowell. 50 participants.

147. March 29, 2015. Provided Powerpoint slide presentation to Eva Antce. Following CalCAN presentation.

148. April 2, 2015. Provided photos to Agronomy Journal Matt Nillson for weed seed bank article CEU training article request.

149. April 9, 2015. Invited presentation to 60 sixth graders of Riverview School, Reedley, CA. Conservation agriculture and my experiences as a scientist. Three back-to-back sessions.

150. April 13, 2015. Invited presentation. Farming practices to reduce risk tied to drought. UC Berkeley. Berkeley Food Institute. Panelist. 100 participants.

151. April 16, 2015. Invited presentation to USDA NRCS State Technical Advisory Committee. Soil health. Davis, CA. 30 participants.

152. April 16, 2015. Conservation agriculture and drought resilience: A tale of two regions. Invited presentation. Department Seminar of Agricultural and Biological Engineering, University of California, Davis. With Amelie Gaudin. 20 participants.

153. April 22, 2015. Invited presentation. Earth Cay. Soil Health in the Vineyard and Field Day. University of California Hopland Research and Extension Center, Hopland, CA. 40 participants.

154. April 25, 2015. Invited presentation. Soil: Get your hands dirty. Two presentations to 50 high school students as part of the 2015 STEM Conference at Reedley College, Reedley, CA.

155. May 9, 2015. Contributed interview text to Dairy CARES. Dairy Today. Regarding Outstanding Achievement in Resource Stewardship from the Innovation Center for US Dairy. Catherine Merlo.

156. May 4 – 7, 2015. Organized and participated in production of five videos with NRCS Soil Health Campaign national video team. Coordinated all of the site shoots that involved Scott Park, Fritz Durst, Michael Crowell, Dan Chellemi, Jess Sanchez, and Alan Sano. Organized, scheduled and wrote background information sheets in conjunction with USDA NRCS Washington, D.C. team.

157. May 14, 2015. Invited presentation. Strategies for increasing soil carbon. CDFA Environmental Farming Act. Science Advisory Panel and Public Comment Meeting. CDFA Building, Sacramento, CA. 100 participants.

158. May 15, 2015. Invited presentations. 2015 AgVentures, Tulare, CA. 270 Fourth graders from Tulare County. World Ag Expo. 270 participants.

159. June 23, 2015. Invited presentations. Fresno County High School STEM Enrichment Program for Orosi, Orange Cove, Parlier, Sanger, Selma, Clovis, Madera, and Kingsburg High Schools. 60 students.

160. June 25, 2015. Organized and hosted field day at Michael Boparai’s Walnut Grove, CA center pivot irrigated tomato field. 10 participants.

161. June 28, 2015. Hosted 2 National Geographic documentary video producers. John Pappas in Five Points, CA.

162. July 27, 2015. Hosted Dirk Lange and Eric Kueneman. FAO, Rome, Italy. Provided and organized field farm tour.

163. August 2015. Invited presentation. UCCE Yolo, Sacramento, and Solano Counties. CASI Center Introductory Presentation. 7 participants.

164. August 17, 2015. Invited presentation. UCCE Kern County. CASI Center Introductory Presentation. 8 participants.

165. September 1 – 3, 2015. Invited panelist on NIFA Challenge Area National Program Panel. Washington, D.C.

166. September 14, 2015. Invited presentation. UCCE Fresno County. CASI Center Introductory Presentation. 9 participants.

We acknowledge that the above list of extension education events related to this CIG project is indeed a tremendous set of accomplishments, but we include this evidence here to reinforce the tremendous value the core work performed in this CIG has had to these diverse outreach opportunities. In addition to these extension education presentations associated with the core work of this project, we also have used this CIG project as a launching board for the California Farm Demonstration Evaluation Network that we have been working with various diverse partners over the course of the past several years to create. This farm demo network effort has been augmented by a State CIG (Agreement - 68-9104-5-344 (SPO #201503328) that was conducted in 2015 – 2016. The overall goals and implementation activities of the network have been modelled after other successful networks including the Soil Health Partnership and the Indiana Conservation Cropping Systems Initiative that have provided background and implementation guidance to our California effort. These goals are identified in figure 1 below.

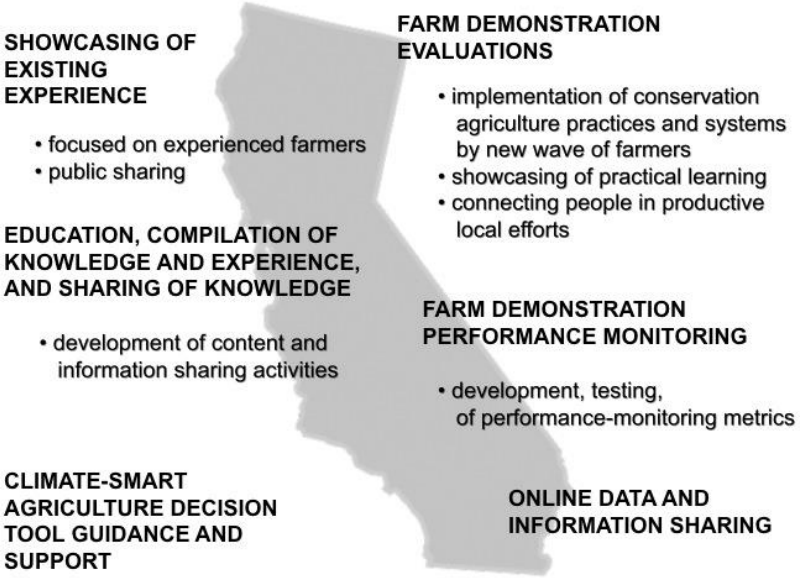

Figure 1. Overall goals and components of California's farm demonstration evaluation network

We wish to point out that the evolution and development of this farm network comes AS A VERY DIRECT RESULT OF THIS NATIONAL CIG PROJECT and that the National CIG project has provided the uniquely important baseline information and training platform that now supports the bulk of the network's information and knowledge base.

2) Objective 2 Soil quality and microbiological properties monitoring

Information developed by this CIG project is the first of its kind for the SJV in California. In each of the following topical summaries of specific work and outcomes of the project, we try to emphasize the functional significance of what was being measured or assayed rather than merely chronicling descriptive findings. Note that we go to the extent of providing these preliminary manuscript summaries that have resulted from this CIG work so as to provide thorough evidence and documentation that a significant amount of directly-related work to this project has been accomplished. We emphasize that the following summaries are still preliminary in nature and are now undergoing final reviews and revisions by our coauthor group unless publication information is provided for those items already in print. Again, we have decided to go into the detail of each of these related items of work on this CIG project to demonstrate the sheer range and depth of work that has now been accomplished as a result of this project.

Tillage and cover cropping affect crop yields and soil carbon in the San Joaquin Valley, California

Agronomy Journal 107(2):597-604. 2015

Abstract

Rising costs and air quality regulations have created interest in California's San Joaquin Valley (SJV) in production systems that reduce tillage operations and soil disturbance. From 1999 – 2009, we evaluated conventional (CT) and reduced tillage (RT) systems for a cotton (*Gossypium hirsutum* L.) / tomato (*Solanum lycopersicon*) rotation with (CC) and without (NO) cover crops in a Panoche clay loam soil in Five Points, CA in terms of yield, soil carbon (C), and the NRCS Soil Conditioning Index (SCI). RT reduced tractor operations by 50% for tomato and 40% for cotton. Cover cropping produced 38.7 t ha^{-1} of biomass. Tomato yields were 9.5% higher in RT versus CT systems and 5.7% higher in NO versus CC systems. CT cotton yields were 10.0% higher than RT yields and 4.8% higher in NO systems, but yield patterns were not consistent from 2005 - 2009. Soil C content was uniform (0-30 cm depth) in 1999 and increased in all systems in 2007. Soil C content of RT and CT systems did not differ, but was greater in CC than in NO systems. In the 0-15 cm depth, RT increased soil C, indicating stratification, and also increased C in the occluded light and mineral fractions. SCI values were positive for RT treatments, predicting a soil C increase, and negative for CT systems, predicting a soil C decline, but measured soil C content increased in all systems. Results show that RT maintains or increases yields relative to CT, and CC stores more soil C than NO.

Introduction

Conservation tillage practices such as no-tillage, strip-tillage, and mulch-tillage are currently used on less than 2% of annual crop acreage in the Mediterranean climate of California's San Joaquin Valley (SJV) (Mitchell et al., 2007). Traditional tillage systems in this region, that consistently includes six of the nation's top ten agricultural production counties (USDA NASS, 2011), have been used since the introduction of irrigation beginning in the late 1930's. These systems enable the predictable production of rotations of crops such as cotton, wheat, safflower, and sugar beets, as well as vegetables, such as tomatoes, melons, onions, lettuce, and garlic. Cropland in the SJV generally has little or no slope and thus concerns about soil erosion have not been a major driver for RT practices as in other regions. In recent years, however, increased diesel fuel prices and interest in reducing labor needs and dust emissions in SJV crop production systems have provided incentives for RT options.

A variety of "minimum-tillage" approaches that consolidate tillage functions and reduce the total number of tillage passes across a field are now being used (Mitchell et al., 2009). These minimum-pass systems rely on combining tillage passes and do not necessarily reduce the overall volume of soil that is disturbed (Reicosky and Allmaras, 2003; Mitchell et al., 2004). Sustained RT practices such as no-tillage (Derpsch et al., 2010) or zone tillage systems (Luna et al., 2011) Shi et al., 2011) and their abilities to increase soil carbon sequestration over time have been reported (Franzluebbers and Follett, 2005; Martens et al., 2005). However, there has been no system developed in the SJV to evaluate the capability of the more classic forms of RT management to reduce production costs or to increase soil C sequestration. Although successful RT systems have been implemented elsewhere for a number of the crops commonly produced in the SJV (Wiatrak et al., 2006; Siri-Prieto et al., 2007; Sainju et al., 2005), these RT systems have been employed in rainfed production regions. The arid SJV receives about 180 mm of rainfall annually and contemporary cropping systems are completely dependent on irrigation. Management of these systems can be complicated by surface plant residues that tend to accumulate in RT fields to higher levels than in CT fields.

In 1999, we began research in Five Points, CA to evaluate RT tomato and cotton systems with and without winter cover crops in terms of productivity, costs, and soil carbon. Following the first four years of this study, no increases were measured in total soil carbon content in the surface 0 – 30 cm of soil, however a redistribution of both carbon and nitrogen from deeper soil into the top 15 cm of soil under RT compared with CT was measured (Veenstra et al., 2006). Similar to other long-term studies with cover crops (Horwath et al., 2002), a significant increase in soil carbon and nitrogen contents was measured in the 0–30 cm layer (Veenstra et al., 2006) in the cover-cropped systems. When averaged over the 2001 to 2003 period (at which point the RT systems had become "established"), tomato yields in the RT system without a cover crop were 13 to 18 t ha^{-1} (16 to 18%) higher than in the other treatments (Mitchell et al., 2009). In cotton, the CTNO yields during this period were the highest of all treatments and were 309 kg ha^{-1} (13%) higher than the RTNO system. As this study proceeded beyond four years, we became more familiar with and were increasingly able to implement RT practices consistently. Our objective in the work reported here was to compare how these tillage and cover cropping systems performed after 10 years of the study in terms of crop yields and soil carbon sequestration.

Materials and Methods

A field comparison of conservation and standard tillage cotton and tomato rotations with and without winter cover crops was established in the fall of 1999 and continued through 2009 at the University of California West Side Research and Extension Center in Five Points, CA. A 20-hectare field in a map unit of Panoche clay loam (fine-loamy, mixed, superactive, thermic

Typic Haplocambids) (Arroues, 2006) was used for the study. A uniform barley (*Hordeum vulgare*) crop was grown over the entire field before beginning the treatments. Prior crop management included a variety of crops, including cotton, wheat for forage, garbanzo beans, garlic, and sugar beets, all of which were conventionally managed, without cover crops. Soil particle size analysis indicated a distinct texture gradient from clay loam (32% clay, 33% silt, 35% sand) at the south end to sandy clay loam (23% clay, 23% silt, 54% sand) at the north end (Baker et al., 2005), and this information was used in blocking treatments along the gradient in the experimental design. The field was divided into two halves; a tomato-cotton rotation was used in one half, and a cotton-tomato rotation was pursued in the other half to allow tomato and cotton plantings and experiments to occur within each year. Management treatments of conventional tillage without cover crop (CTNO), conventional tillage with cover crop (CTCC), reduced tillage without cover crop (RTNO), and reduced tillage with cover crop (RTCC) were replicated four times in a randomized complete block design in a factorial manner on each half of the field. As customary throughout the SJV, raised beds were used for both tomato and cotton production systems. Treatment plots consisted of six beds, each measuring 9.1 x 82.3 m. Six-bed buffer areas separated tillage treatments to enable the different tractor operations that were used in each system. A cover crop mix of Juan triticale (*Triticosecale* Wittm.), Merced ryegrain (*Secale cereale* L.), and common vetch (*Vicia sativa*) was planted at a rate of 89.2 kg ha^{-1} (30% triticale, 30% ryegrain, and 40% vetch by weight) in late October in the CTCC and RTCC plots and irrigated once in 1999 with 10 cm of water to establish the crop. In each of the subsequent years, the cover crops were planted in advance of winter rains, however, no irrigation was applied due to concerns about the cost and availability of additional water that would be needed to grow a cover crop. The cover crops were chopped in mid-March of the following years using a Buffalo Rolling Stalk Chopper (Fleischer, NE). In the CTCC system, the chopped cover crop was disked into the soil to a depth of about 20 cm, and 1.52 m-wide beds were formed prior to tomato transplanting or cotton seeding. The chopped cover crop in the RTCC system was sprayed with a 2% solution of glyphosate (N -(phosphonomethyl)glycine) after chopping and left on the surface as a mulch.

Conventional intercrop tillage practices that break down and establish new beds following harvest were used in the CT systems (Tables 1 and 2). The RT systems were managed from the general principle of trying to reduce primary intercrop tillage to the greatest extent possible. Controlled traffic farming, or zone production practices that restrict tractor traffic to certain furrows were used in the RT systems, and planting beds were not moved or destroyed in these systems during the entire study period.

In the tomato-planted half of the field, a common commercial variety in the SJV, ‘8892,’ was transplanted in the center of beds at an in-row spacing of 30.5 cm and a final population of 21,581 plants ha^{-1} during the first week of April in each year using a modified three-row commercial transplanter fitted with a large (50 cm) coulter ahead of each transplanter shoe. Treatments received the same fertilizer applications with dry fertilizer (11-52-0 NPK) applied preplant at 89.2 kg ha^{-1} (9.8 kg ha^{-1} N and 46.4 kg ha^{-1} P) using a standard straight fertilizer shank at about 15 cm below the transplants. Additional N (urea) was side dress applied at

111.5 kg ha^{-1} for a total of 51.3 kg N ha^{-1} in two lines about 18 cm from the transplants and about 15 cm deep about four weeks after transplanting.

The RoundUp Ready™ transgenic upland cotton variety ‘*Riata*’ was used from 2000 - 2007 in all cotton systems and was established using a John Deere (Moline, IL) 1730 No-till Planter. In 2008 and 2009, an experimental RoundUp Ready Flex™ Pima variety, ‘Phy-8212 RF, ‘was grown. Approximate plant populations in all years were 148,000 ha^{-1}. Dry preplant fertilizer (11-52-0) was applied at 224 kg ha^{-1} using shanks at about 20 cm depth and then mixed throughout the CT beds using bed preparation tillage implements (Table 1) and shanked in the RT systems (Table 2).

Table 1. Comparison of conventional tillage (CT) and reduced tillage (RT) system operations with and without cover crops used in this study for tomato. (Each “X” indicates a separate instance of each operation.)

	With cover crop		Without cover crop	
Operation	CT	RT	CT	RT
Shred cotton	X		X	
Undercut Cotton	X		X	
Disc	XXXX		XX	
Chisel	X		X	
Level (Triplane)	X		X	
List beds	XX		X	
Incorporate/Shape beds	X		X	
Clean Furrows		X		X
Shred Bed		X		X
Spray Herbicide: Treflan	X		X	
Incorporate Treflan (Lilliston)	X		X	
Spray Herbicide: Roundup			X	X
Spray Herbicide: Shadeout	X	X	X	X
Cultivate – Sled Cultivator	XXX		XXX	
Cultivate – High Residue Cultivator		XXX		XXX
Plant Tomatoes	X	X	X	X
Fertilize	XX	XX	XX	XX
Plant Cover Crop	X	X		
Mow Cover Crop	X	X		
Harvest-Custom	X	X	X	X
Times Over Field	23	12	19	11

Table 2. Comparison of conventional tillage (CT) and reduced tillage (RT) operations with and without cover crops used in this study for cotton. (Each “X” indicates a separate instance of each operation.)

	With cover crop		Without cover crop	
Operation	CT	RT	CT	RT
Disk	XX		XX	
Chisel	X		X	
Level (Triplane)	X		X	
List beds	X		XX	
Spray Herbicide: Treflan	X		X	
Incorporate Treflan (Lilliston)	XX		XX	
Spray Herbicide: Roundup	XX	XXX	X	XXX
Cultivate – Rolling Cultivator	XX		X	
Chain Beds	X	X		
Plant Cotton	X	X	X	X
Fertilize	X	X	X	X
Plant Cover Crop	X	X		
Mow Cover Crop	X	X		
Spray Insecticides/Growth Regulation	XX	XX	XX	XX
Spray: Defoliate	X	X	X	X
Spray Insecticides	XX	XX	XX	XX
Harvest-Custom	X	X	X	X
Times Over Field	23	14	19	11

The basic equation

$$ETc = Kc \cdot ETo$$

where ETc is the projected evapotranspiration of the tomato crop, Kc is a corresponding growth-stage dependent crop coefficient, and ETo is reference evapotranspiration for a given production region (Hanson and May, 2005; Hanson and May, 2006) was used to schedule furrow irrigations of both crops throughout the study. ETo data were acquired from a California Irrigation Management Information System (CIMIS) (http://wwwcimis.water.ca.gov/cimis/welcome.jsp) weather station located about 200 meters from the study field. Crop coefficient (Kc) values were based on crop canopy estimates for each irrigation plot. Applied water amounts averaged about 71 cm ha^{-1} for tomato and 61 cm ha^{-1} for cotton, which are close to historical estimates for ETc and commercial application volumes in the region (Hanson and May, 2006). An additional application of 124.9 kg ha^{-1} of urea fertilizer per acre was made at the time when plants were about to cover the entire soil surface or just before they would have been too large for tractor intervention in each year in each system using a fertilizer shank fitted with a 45.7 cm coulter to cut residues about 25 cm to the side of plants and about 15 cm deep. All tractor traffic was restricted to the furrows between planting beds in the RT systems; no tillage was done in the RT plots following tomatoes and preceding the next cotton crop, and only two tractor passes were conducted following cotton and preceding each subsequent tomato crop. These operations included shredding and uprooting the cotton stalks in order to comply with "plowdown" regulations for pink bollworm (*Pectinophora gossypiella*) control in the region and a furrow sweep operation to clean out furrow bottoms to improve irrigation water movement down the furrows. Tomato yields were determined in each year using field-weighing gondola trailers following the commercial machine harvest of the inner two beds in each six-bed plot. Cotton lint yields were determined using seed cotton weights from the inner four rows in each twelve-row plot multiplied by gin turnout percentages determined on samples sent through the University of California Shafter Research and Education Center research gin. Crop residues were worked into the soil following harvest in the CT systems and left on the soil surface in the RT systems. Aboveground tomato, cotton, and cover crop residue was determined on November 25, 2002 and December 20, 2003 by collecting all loose surface plant material in a 1-m^2 area in each plot, drying at 58°C to constant weight, and weighing. Following an average 141-day winter growing period, cover crop biomass was harvested in mid-March of each year by collecting all aboveground plant material in a 1 m^{-2} area of each plot, drying at 58°C generally for 4 – 5 days to constant weight, and weighing. Percent surface residue was determined using the line-transect method on April 20, 2004 and December 18, 2009 (Bunter, 1990), and surface residue biomass was determined on November 25, 2002 by collecting, drying and weighing all material within a 1 m^{-2} area in each plot.

Soils were sampled in 1999 and 2007 at two depths (0 to 15 cm and 15 to 30 cm) in the fall after harvest. Six to eight 7.6-cm-diameter cores per depth were taken in each plot and composited before air drying, sieving through a 2 mm sieve and grinding using a soil pulverizer to pass through a 60 mesh screen according to protocols of the University of California, Davis Analytical Laboratory (http://anlab.ucdavis.edu/sampling/soil-sampling-and-preparation). From these samples, total carbon (C) and total nitrogen (N) were measured by combustion using a combustion C analyzer (CE Elantech, Inc., Lakewood, NJ). Particulate soil carbon fractions (free light, occluded, and mineral) were isolated by the methods of Sohi et al. (2001). Briefly, the free light fraction is floated on NaI, the occluded fraction is floated on NaI after sonication, and the mineral fraction is the remainder. The C concentration of these fractions was also measured by combustion. Bulk density was measured by the compliant cavity method (USDA NRCS, 2004) for the two depths in 2003 and in 2007. For total C calculations in 1999, at the beginning of the study, we used the bulk density data for the CTNO treatment in 2003. The research plot used for this study had been under conventional management practices prior to the study, so we assumed that bulk densities in 1999 were similar to those we measured in 2003. For total C calculations for 2007, we used the bulk densities measured for each sampling site.

A calendar of operations was maintained for each of the systems, and the equipment used and materials applied were recorded. Specific management practices described above and in Tables 1 and 2 and tomato and cotton yields were used to estimate soil loss using the Revised Universal Soil Loss Equation (RUSLE) 2, to compute the soil condition index (SCI) and the soil tillage intensity index (STIR), and to estimate fuel use of each tillage / cover crop management system using procedures described in the USDA NRCS National Agronomy Manual Part 508 (USDA NRCS, 2002) and summarized by Zobeck (2007, 2008). The SCI is a predictive tool used to estimate impacts of management on SOM contents (USDA NRCS, 2003). It takes into account biomass production, field operations, and erosion rates and gives an overall rating of the trend of SOM. The STIR is calculated using RUSLE2. Higher STIR values reflect higher tillage intensity. The SCI and STIR predictive soil management index tools are required in several USDA Natural Resource Conservation Service (NRCS) criteria that are used to assess applications for Environmental Quality Incentives (EQIP) and Conservation Security Programs (CSP) of the Farm Security and Rural Investment Act of 2002 (Zobeck et al., 2007 and 2008).

Data were analyzed using PROC Mixed procedures with tillage and cover crop as fixed variables and years and replication as random variables using SAS statistical software (SAS Institute, 2002). Year was considered a random variable as the crops were rotated between the two experimental blocks each year. Interactions between years and the factors were also tested. Whenever there was a significant interaction between year and the factors, data were separated by years and re-analyzed. The significance level for the variables and their interactions was set at 0.05. Prior to the analysis, assumptions of ANOVA were tested. Data on cover crop biomass failed to meet the assumptions and were, therefore, square-root transformed prior to analysis. Whenever ANOVA showed significant differences ($P<0.05$), means were separated using either Fisher's Protected Least Significant Difference method or the pdiff option in SAS. Mean separation was based on transformed data, but non-transformed means were presented for clarity.

Results and Discussion

The number of tractor trips across the field was reduced by about 50% for tomato (Table 1) and 40% for cotton (Table 2) in the RT systems relative to the CT approaches. The reduction in the number of trips has been shown to reduce the amount of dust emitted in the field (Baker et al., 2005). Differences in the tillage intensity between systems were due primarily to reductions in soil-disturbing operations commonly associated with postharvest land preparation, including disking, chiseling, leveling and relisting beds, operations that are typically performed in the fall. The operations listed in Tables 1 and 2 represent average sequences for all years; slight differences occurred in certain years. For instance, we originally performed two operations subsequent to cotton harvest in the RT systems: a one-pass Shredder-Bedder (Interstate Mfg., Bakersfield, CA) to shred and undercut the cotton plant, and a furrow sweeping operation using a Buffalo 6000 High Residue Cultivator (Fleischer Mfg., Columbus, NE) modified and fitted with only furrow implements. However, since 2003, we fitted our no-till tomato transplanter with furrow "ridging wings" and thereby cleared out residues from furrow bottoms at the time of transplanting and only performed a cotton stalk shredding using a flail mower and a root pulling operation (Sundance Wide Bed Disk, Coolidge, AZ) following cotton harvest.

Cover crop biomass and surface residue

Amounts of cover crop biomass produced during the study varied widely (Tables 3 and 4) (See Table 3 at end of report on landscape page) and closely corresponded to rainfall (Figure 1).

Figure 1 Average monthly precipitation (cm), potential evapotranspiration (ETo, cm), and average monthly temperatures (°C) for Five Points, CA study site

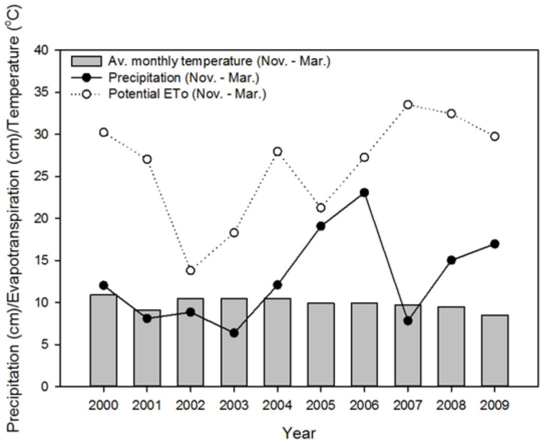

Table 4. Effect of previous crop and tillage type (RT - reduced tillage, CT – conventional tillage) on cover crop biomass production from 2000 through 2009 in Five Points, CA

Cover crop biomass[†] kg ha^{-1}	
Previous crop[±][◊]	Tillage type[±]
Fallow (1999-2000 only)	RT
9345 (259) a	4098 (354) a
Cotton	CT
2812 (289) c	3609 (316) b
Tomato	
3509 (225) b	

[†] Values are means + standard errors of the means.

[±] Within columns, means followed by the same letter are not significantly different (*P*>0.05)

[◊] ANCOVA conducted on square root transformed data using previous crop in the plots as a covariate.

In 1999 – 2000, the cover crop was sprinkle-irrigated in order to establish the experimental treatments, however, in each of the following years, cover crop establishment and growth depended on winter rain reflecting more accurately what farmers in the region would most likely do in the face of uncertain water supplies and sustained drought. With the exception of 1999 – 2000, annual cover crop biomass averaged 3167 kg ha^{-1} year^{-1} during the rainfed period. This production is on average about one-third of what might be expected in this region when supplemental irrigation is used during the winter, as was done in 1999 – 2000 (Mitchell et al., 1999), and was generally higher in winters with greater rainfall, although there was no significant correlation between total precipitation and cover crop biomass. Biomass data for the three years, 2005 – 2007, illustrate this finding. In 2005, the highest biomass (other than in 2000 with supplemental irrigation) was attained with the second highest total November to March precipitation and in 2007 the lowest biomass was recorded with the second lowest precipitation. However, in 2006, which had the highest total winter rainfall, only a low-intermediate level of biomass was produced. These long-term relationships between cover crop biomass and precipitation suggest that it is not only winter seasonal total precipitation, but also likely the timing of precipitation that is important to sustain largely rainfed cover crop biomass accumulation.

Cover crop biomass was significantly different between years. Both tillage type, CT or RT, and previous crop affected cover crop biomass (Table 4), however, there was no interaction between tillage type and previous crop and year and tillage type. Greater cover crop biomass was achieved following tomato than cotton, probably due to higher rootzone residual soil water content following tomato as compared to the longer-season cotton. There was also greater biomass produced in the RT system than in the CT system, suggesting that greater stored soil water was available in the reduced disturbance RT plots relative to the CT plots that were tilled each fall ahead of cover crop seeding (Mitchell et al., 2012). Over the ten-year period of this study, a total of 38.7 t ha^{-1} of dry biomass was produced with 10 cm of supplemental irrigation. Surface residue biomass in the RT systems was significantly higher than in both the CTNO and CTCC treatments after two years (Table 5). Residue % cover averaged 6 (CTNO), 9 (CTCC), 64 (RTNO), and 89 (RTCC) across the two sampling times and represent, we believe, the first published data set of high residue cropping systems in California (Table 5).

Table 5. Percent surface residue and surface residue biomass for tillage and cover crop treatments in Five Points, CA

	% Surface Residue Cover[†]		*Surface Residue Biomass Weights*[†]
Treatment[¥]	*20-Apr-04*	*18-Dec-09*	*25-Nov-02*
	- - - - - - - - - - - - - %	*- - - - - - - - - - - - - -*	*- - - - - kg - - - - -*
RTCC	*88 (4) A*[§]	*91 (0.71) A*	*794 (417) A*
RTNO	*42 (7) B*	*89 (1.55) A*	*757 (295) A*
CTCC	*11 (0.5) C*	*6 (1.68) B*	*179 (163) B*
CTNO	*3 (0.2) D*	*5 (2.56) B*	*98 (106) B*

[¥] *CT – conventional tillage, RT = reduced tillage, CC = winter cover crop, NO = no winter cover crop.*

[†] *Values shown are the average of four replicate values with ± one standard deviation of the average given in parentheses.*

[§] *Means with the same letter are not significantly different, Fisher's least significant difference, (P > 0.05).*

Tomato productivity

Excluding the period 1999 – 2000, during which time the treatment effects were becoming established, tillage affected tomato yields in four out of the remaining nine years of the study (Table 6). In each of these four years (2002, 2003, 2004, and 2006), tomato yield were greater in the RT than in the CT treatments, whereas in 2000, 2005, 2007 and 2008 tomato yields were similar between the two tillage systems. However, in 2001 and 2009, there was an interaction between the tillage system and the cover crop. In 2001, the CTCC plots had greater tomato yields than in the CTNO plots, but cover crops had no effect on tomato yields in the RT plots. Contrary to 2001, the effect of cover crops was observed in 2009 only in the RT systems, where the presence of cover crop in this tillage system had lower tomato yields than the plots without cover crops. Similarly, cover crops affected tomato yields in three (2000, 2002, and 2005) out of the nine years of the rotation. In each of these years, plots with no cover crops resulted in higher tomato yield than the plots with cover crops. No such differences were observed in 2003, 2004, 2006, 2007, and 2008.

Table 6. Processing tomato yields for conventional and reduced tillage systems with and without cover crops, Five Points, CA, 2000 to 2009.

	Tomato yield (t ha^{-1})									
Treatment	2000[a]	2001[b]	2002[a]	2003[a]	2004[a]	2005[a]	2006[a]	2007	2008	2009[c]
Tillage										
RT	120.2	-	112.4 a	120.2a	113.3 a	101.3	101.6 a	89.9	107.2	-
CT	125.6	-	100.0 b	97.5 b	98.9 b	102.5	62.0 b	89.9	110.3	-
Cover crop										
Cover	117.8 b	-	98.0 b	110.1	101.1	94.6 b	81.1	87.4	109.7	-
No cover	128.1 a	-	114.4 a	114.4	110.8	109.4 a	82.7	92.4	107.9	-
RTCC	-	139.3	-	-	-	-	-	-	-	111.9 b
RTNO	-	145.8	-	-	-	-	-	-	-	120.2 a
CTCC	-	142.2 a	-	-	-	-	-	-	-	115.1
CTNO	-	131.5 b	-	-	-	-	-	-	-	110.3
ANOVA	Significance level (Pr>F)									
Tillage	0.0785	0.1190	0.0194	<0.0001	0.0115	0.7684	0.0001	0.9143	0.1865	0.1777
Cover crop	0.0033	0.5370	0.0047	0.4300	0.0638	0.0053	0.7319	0.2169	0.4814	0.4660
Tillage X Cover crop	0.3494	0.0295	0.0996	0.0768	0.8999	0.2094	0.2705	0.0920	0.3127	0.0194

[a] Means followed by different letters within a column averaged for tillage or cover crop are significantly different according to Fisher's protected LSD at an 0.05 level of significance.

[b] Interaction between tillage and cover crop was caused because cover crop had a significant effect in CT but not in RT. Therefore, means followed by different letters for CTCC and CTNO are significantly different according to Fisher's protected LSD at an 0.05 level of significance.

[c] Interaction between tillage and cover crop was caused because cover crop had a significant effect in RT but not in CT. Therefore, means followed by different letters for RTCC and RTNO are significantly different according to Fisher's protected LSD at an 0.05 level of significance.

Table 7. Cotton yields for conventional and reduced tillage systems with and without cover crops, Five Points, CA, 2000 to 2009.

	Cotton yield ($t\ ha^{-1}$)									
Treatment	2000[a]	2001[b]	2002[c]	2003[a]	2004[a]	2005[a]	2006[a]	2007	2008	2009
Tillage										
RT	285.6	-	-	1107.9 b	1651.1 b	1490.8	1196.6	2023.3 b	456.4 a	755.9
CT	346.5	-	-	1281.9 a	2013.9 a	1561.5	1259.8	2117.6 a	327.9 b	708.6
Cover crop										
Cover	352.5	-	-	1246.5	1738.1 b	1539.4	1177.8	2099.4	402.6	763.8
No cover	279.6	-	-	1143.3	2016.9 a	1512.9	1278.6	2041.5	381.6	700.8
RTCC	-	1565.5	1251.8 b	-	-	-	-	-	-	-
RTNO	-	1646.3	1736.3 a	-	-	-	-	-	-	-
CTCC	-	1505.7 b	1920.5	-	-	-	-	-	-	-
CTNO	-	1860.8 a	1929.5	-	-	-	-	-	-	-
ANOVA	Significance level (Pr>F)									
Tillage	0.2952	0.0173	<0.0001	0.0112	0.0041	0.1582	0.2631	0.0160	0.0391	0.3180
Cover crop	0.2161	<0.0001	<0.0001	0.0919	0.0434	0.5785	0.0888	0.1032	0.7027	0.1923
Tillage X Cover	0.1030	0.0010	<0.0001	0.9363	0.6745	0.4069	0.8777	0.0982	0.3524	0.9957

crop

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[a] Means followed by different letters within a column averaged for tillage or cover crop are significantly different according to Fisher's protected LSD at an 0.05 level of significance.

[b] Interaction between tillage and cover crop was because cover crop had a significant effect in CT but not in RT. Therefore, means followed by different letters for CTCC and CTNO are significantly different according to Fisher's protected LSD at an 0.05 level of significance.

[c] Interaction between tillage and cover crop was because cover crop had a significant effect in RT but not in CT. Therefore, means followed by different letters for RTCC and RTNO are significantly different according to Fisher's protected LSD at an 0.05 level of significance.

Table 8. Soil carbon mass for tillage and cover crop treatments† at two soil depths at the start of the study in the fall of 1999 and in the fall of 2007.

	1999			2007	
Depth (cm)	Treatment	Mean§ (t ha^{-1})	Depth (cm)	Treatment	Mean§ (t ha^{-1})
0 - 15	RTCC	9.33 (0.18, A)	0 - 15	RTCC	16.20 (0.53, A)
	CTCC	9.25 (0.40, A)		CTCC	12.69 (0.29, AB)
	RTNO	9.27 (0.41, A)		RTNO	13.13 (0.46, AB)
	CTNO	8.87 (0.31, A)		CTNO	10.84 (0.19, B)
15 - 30	RTCC	10.39 (0.30, A)	15 - 30	RTCC	12.91 (0.62, AB)
	CTCC	10.66 (0.99, A)		CTCC	13.67 (0.65, A)
	RTNO	11.40 (1.11, A)		RTNO	10.96 (0.51, B)
	CTNO	9.69 (0.52, A)		CTNO	11.81 (0.31, AB)
Total	RTCC	19.71 (0.45, A)	Total	RTCC	29.11 (0.94, A)
	CTCC	19.91 (1.20, A)		CTCC	26.36 (0.78, AB)
	RTNO	20.67 (1.03, A)		RTNO	24.09 (0.81, BC)
	CTNO	18.57 (0.75, A)		CTNO	22.65 (0.26, C)

† CT = conventional tillage; RT = reduced tillage; NO = no cover crop; CC = winter cover crop.

§Values in parentheses are standard error of the means (n = 8).
Within a column, means followed by the same letters are not significantly different using a one-way ANOVA analysis with Tukey HSD means comparison.

Higher tomato yields in the NO systems relative to the CC systems may have resulted from greater difficulties we experienced in no-till transplanting tomatoes into the generally higher surface residue conditions of the CC systems (Table 5). Also soil nitrogen sequestration may have occurred in the CC systems. The cover crops were predominantly composed of more triticale and rye relative to the legume, vetch, and had an average C:N ratio that averaged 42:1.

. While not quantified, observations of early-season tomato growth in the CC system indicated slower initial growth in these systems that may also have been attributable particularly in the RTCC system to both lower above- and below-residue temperatures (Mitchell et al., 2012). As discussed earlier, cover crops interacted with the tillage system in 2001 and 2009. In summary, the RT system generally resulted in greater or similar tomato yields compared to CT in most years of the study. We speculate that yields in the RT systems were maintained relative to the CT system despite the fact that very little intercrop tillage was used because adequate transplant populations were achieved, beneficial changes in soil properties and function were achieved in the RT systems that led to improved tomato crop growth. Similarly, presence of a cover crop generally resulted in lower or similar tomato yields in most years of the study. Therefore, it can be concluded that tomato yields can be maintained or increased by using RT systems under the conditions and time frame of this study. Further, use of this cover crop program will not have direct effects in increasing tomato yields, but rather yields will be compromised.

Cotton productivity

Similar to the results for tomato, yield differences in cotton yield due to the treatments were not consistent in each year of the study (Table 7). Following the establishment of the tillage and cover crop comparisons after the first summer crops in 2000 and up to 2008 when the Pima cotton variety was grown, cotton yields were greater in the CT plots than in the RT plots in 2003, 2004, and 2007. While cotton yield was similar between the two tillage systems in 2000, 2005, 2006, and 2009, there was interaction between tillage system and the presence of a cover crop in 2001 and 2002. In 2001, the presence of a cover crop resulted in lower cotton yield in the CT system but not in the RT system. Contrary to 2001, cover crop resulted in lower cotton yield in the RT system, but had no effect on yield in the CT system. As mentioned in the discussion for tomato, crop establishment effects and their interaction with the tillage or cover crops may have resulted in these differential effects in certain years of the study. Cover cropping itself had no consistent effect on cotton yield. On the other hand, CT systems generally resulted in greater or similar cotton yields compared to the RT systems, although in most years the difference was not significant. Only in one year of the entire study did the RT systems result in greater yields than the CT systems. Overall, we conclude that the CT systems produced slightly higher cotton yields than the RT systems, and cover crops had no consistent effect on cotton yield. Interactions between tillage system and cover cropping were also not consistent.

In the 2000 season, all cotton system yields were low due to a devastating infestation of mites (*Tetranynchus urticae* Koch) that persisted all season, exacerbated by likely pesticide resistance problems that developed with repeated miticide application (Mitchell et al., 2008). During the 2008 and 2009 seasons, the Pima cotton variety, ‘Phy-8212 RF,’ was grown, and yields were lower for all treatments than in prior years. The relatively aggressive indeterminate growth habit of the Pima variety presented a significant change from the Acala variety. Pima with this growth habit can be more difficult to manage for high yields unless the right combination of plant growth regulator and deficit irrigation management are used to control vegetative crop growth (Munk et al., 2008), and the result was reduced yield in the Pima part of this study. This variety of cotton was used to follow the Acala cotton work to gain RT experience with Pima cotton and because Pima is an increasingly attractive and economically viable cotton variety option for SJV producers. If it is necessary to water stress the Pima variety to control vegetative growth, it is likely that it would respond negatively to systems with more soil water. Thus, it would be necessary to manage treatments separately relative to water applications with the net result being similar yield with less water in the RT systems.

Soil carbon

Soil bulk density is important in the interpretation of changes in soil C. Often total soil C is measured on a mass-per-mass basis (%); however, using this method, soils with similar C percentages, but different bulk densities, would have different total soil C contents on a mass-per-volume basis (Veenstra et al., 2007). We did not measure bulk density in 1999. As described in the methods section, we measured the bulk density in 2003, and assumed that the 2003 CTNO bulk densities reflected conditions at the beginning of the field experiment. We used average values of 1.24 g cm^{-3} (0-15 cm) and 1.35 g cm^{-3} (15-30 cm) to calculate initial soil C stocks. For total C calculations for 2007, we used the bulk densities measured for each sampling site. In 2007, average soil bulk density (g cm^{-3}) in the 0 – 15 cm depth were as follows: 1.25 RTCC, 1.25 RTNO, 1.25 CTCC, and 1.20 CTNO, and in the 15-30 cm depth: 1.49 RTCC, 1.49 RTNO, 1.43 CTCC, and 1.32 CTNO. Thus, treatments had little effect on bulk density in the 0-15 cm depth, but RT treatments, in particular, produced an increase in bulk density in the 15-30 cm depth, presumably due to the lack of tillage disturbance at that depth.

After eight years of the tillage and cover crop treatments, soil carbon content in the 0-to-30-cm depth increased relative to initial conditions in 1999 for all treatments (Table 8). The RTCC treatment had the highest soil C content of all treatments, but did not have a significantly higher content than the CTCC treatment. Similarly, the RTNO soil C content was not significantly different from the CTNO treatment. Thus, increased soil C storage appears to be the result primarily of the cover crop treatment, rather than the reduced tillage treatment, although the combination of the two treatments (RTCC) resulted in significantly higher soil C stocks than the CTNO treatment. The degree of stratification of soil carbon with depth, expressed as a ratio, has been proposed as an indicator of soil quality or soil functioning that may be useful for comparing management impacts on soils that differ in inherent carbon levels (Franzluebbers, 2002). Stratification ratios (0 – 15 cm / 15 – 30 cm) of soil C were 0.92 for the CTNO and CTCC systems, 1.20 for the RTNO system, and 1.25 for the RTCC system, clearly demonstrating the effect of not incorporating residues in the RT treatment. Franzluebbers (2002) hypothesized that sustained RT management would produce larger ratios than CT management, but also suggested that even larger differences might be expected in regions such as California with high temperatures, irrigation and inherently low soil C stocks. The RT systems resulted in larger stratification ratios than those in the CT systems, but the ratios are probably not as high as could be achieved in a no-till system. Our RT experimental systems relied on a number of soil disturbing operations such as cultivation for tomatoes and postharvest stalk management for cotton, so some mixing of soil C into the 15-to-30 cm depth probably occurred, thereby reducing the stratification ratio.

Treatment effects on the distribution of particulate soil carbons fractions varied (Table 9). The free light fraction C content was similar among all treatments and depths with the exception of the RTCC treatment where light fraction C content was higher in the 0-15 cm depth than in the 15-30 cm depth. RT treatments generally resulted in higher C contents in the occluded light fraction and the mineral fraction compared to CT treatments, and the effect was most pronounced in the 0-15 cm depth, compared to the 15-30 cm depth. These results suggest that RT practices may result in soil C storage pools that turn over more slowly than C pools in soils under CT practices, although the effect is limited to the near-surface layer due to the lack of mixing by tillage operations.

Soil conditioning index

The SCI has been proposed by NRCS as a predictor of the consequences of management actions on soil organic carbon, but has recently been shown to be more closely associated with a more labile form of soil organic carbon known as particulate organic matter, or POM-C, as well as what have been termed the residue equivalent value (REV) that drives organic matter accumulation in the soil. The NRCS currently uses the SCI as one of its criteria for practice standards including Conservation Crop Rotation and Residue Management and for determining eligibility for Farm Bill conservation programs such as EQIP and CSP (Zobeck et al., 2007). The computed SCI values in Table 10 seem to be closely associated with the field operations that were used in the farm tillage and cover crop systems (Tables 1 and 2). The SCI values were negative for the two CT systems and positive for the RT systems indicating that the level of SOM is predicted to increase under RT and decrease under CT management (Table 10). The lower STIR values calculated using RUSLE2 for the RT systems indicate potentially desirable soil outcomes such as lower carbon losses from soil to the atmosphere, less soil consolidation, and higher infiltration rates (USDA NRCS, 2012).

Our results contrast somewhat with the SCI predictions in that soil C content increased with all treatments. The soil C increase in the CTNO treatment may reflect the effect of a change in management inputs beginning in 1999 (start of the experiment) compared to the prior long-term management of the experimental plots, wherein a variety of low biomass crops were grown (e.g., cotton without tomato), or where most crop residues were removed during harvest (green wheat chopped for feed). The soil C increase may reflect an inherent capacity for these soils to store C, if crops with higher biomass production are grown. Further, our conventional tillage system allowed tillage in only one direction in order to preserve the beds of adjacent treatments. This management approach contrasts with large-scale conventional tillage, where fields are often tilled in two directions (often in an orthogonal pattern). As a result, we speculate that crop residues, even in the CTNO treatment, were concentrated in the row and led to an increase in soil C content. This result is somewhat of an artifact of our experimental set-up, and may partly explain why our soil C results contrast with the SCI predictions. Lastly, the SCI places considerable emphasis on tillage operations. Given that our RT treatments reduced the number of operations by about half, compared to the CT treatments, the SCI may overestimate the relative STIR of the two systems and over-predict C loss in the CT treatments.

Implications for row crop management in the San Joaquin Valley

The general RT approach pursued in this study was to more severely restrict tillage operations than is customarily done today throughout the SJV. As a result of this, more residues accumulated on the soil surface, particularly in the RTCC systems (Table 5). This at least partly explains the lower numbers of cotton plants that were established in this system during the first four years of the study due to difficulties at seeding as well and the lower yields in this system early in the study (Mitchell et al., 2008). In addition, we were initially concerned that residues would interfere with the action of the "over-the-top" tomato herbicide *rimsulfuron* (1-(4,6-dimethoxypyrimidin-2-yl)-3-(3-ethylsulfonyl-2-pyridylsulfonyl)urea), which can be sprayed after transplanting and sprinkled in to activate. By 2003, however, this herbicide was used in all systems with observed benefits. For RT cotton, we relied solely on one or two in-season applications of glyphosate; no cultivation was done in these systems. For all tomato treatments, we typically cultivated two to three times, but based on visual estimates of weed populations, this did not achieve a comparable level of weed control in the RT systems as in the CT systems in all years, and this is one aspect of our RT approach that needs future attention.

It is important to point out that while the RT systems we employed in this study dramatically reduced overall tillage and soil disturbance relative to the CT norms for the SJV, they by no means constitute what is customarily considered "no-till" production. In classic no-till, or "direct seeding" systems, crops are planted directly into residues and no additional soil disturbance is generally done prior to harvest. We employed an intermediate or incremental tillage reduction strategy in part to clear channels for irrigation water movement down furrows and in part to meet California Department of Food and Agriculture (CDFA) mandates for pink bollworm (PBW) pest control in cotton. Current CDFA regulations require uprooting cotton roots post-harvest and residue mixing with the soil. Recent changes in the CDFA PBW Control and Eradication Program allow for reduced post-harvest tillage in cotton fields with no PBW findings, or in fields outside of a nine square mile radius from a PBW trapping find. These changes should make it easier to adopt RT practices in cotton rotations in the SJV.

In summary, the long-term aspect of this study has been quite valuable in providing information on the variable nature of rainfed cover crop biomass production in this region. It has revealed challenges and opportunities for improving tomato and cotton productivity under the RT, high residue management that was used. Finally, it provided the first demonstration of the potential for increasing soil carbon stocks in the semi-arid SJV with cover crops and RT. The alternative practices that were pursued over the course of this work borrowed heavily from the core principles of various sorts of conservation agriculture systems that have been developed around the world, but that are yet to be used in the historically very productive SJV.

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Conservation tillage and cover cropping shift microbial communities from competitor to ruderal life strategies in a Mediterranean climate agricultural soil

In preparation for submission to appropriate peer-reviewed journal

Abstract

This study evaluated microbial communities from a long term field-size study of Mediterranean climate, irrigated soil under four tillage treatments – conservation tillage, conservation tillage plus cover crop, standard tillage, and standard tillage plus cover crop – in a tomato/cotton rotation. Soil DNA samples from three depths 0-5, 5-15, and 15-30 cm were analyzed by quantitative PCR and Illumina sequencing and compared to soil physical and chemical data available for the site. Total bacterial numbers were higher in the cover crop treatments at all depths compared to no cover crops, while no till treatments showed higher numbers in 0-5 cm but lower numbers at lower depths compared to standard tillage. Treatment and depth effects were limited for archaea numbers. Overall, the presence or absence of cover crops appeared to play the most important role in shaping microbial community function. No cover crop + till treatment enriched for competitors, no cover crop + no till treatment enriched for stress tollerators, and the cover cropped treatments enriched for ruderals. These findings are consistent with soil physicochemical conditions at the site and provide a framework for interpreting the development and functional properties of the soil communities under the four different treatments.

Introduction

The transformation of natural habitats to agricultural ecosystems is typically accompanied by significant loss, up to 50%, of soil organic matter (SOM) (Kirkby et al. 2014). Stopping and potentially reversing this trend is an important challenge at all scales, from local to global. Globally, the SOM pool contains more than three times as much carbon as either the atmosphere or terrestrial vegetation pools. In addition to be a significant carbon sink, SOM is also intimately involved in the creation and maintenance of soil structure, and its formation both shapes and is shaped by resident microbial communities. Reduced tillage has been suggested as a practice aimed to protect, conserve and improve soil structure and SOM in agriculture, either as a stand-alone conservation practice or in combination with cover cropping or other increased plant matter incorporation techniques.

The effects of reduced tillage and cover cropping have been studied extensively in rain fed systems, but the effects of these practices on arid, irrigated soils have been less well documented (Mitchell et al 2015). A field scale conservation tillage and cover cropping experiment has been in place at the UC Davis West Side Research and Extension Center (Research Center) at Five Points, CA since 1999 (Mitchell et al. 2015)(other Jeff refs?). At the time of the soil microbial community characterization described in this paper, conservation till and/or cover cropping treatments resulted in total soil C 12-83% higher and total soil N 13-67% higher in comparison to standard till with no cover crops (Dhainaut Medina 2015), as well as 66-147% higher water-stable aggregates, and improved performance in other soil structure characterization tests such as water infiltration and slake tests (Mathesius 2015). The combined conservation till and cover crop treatment showed the greatest change from the standard till, no cover crop treatment in virtually all parameters under study (Dhainaut Medina 2015; Mathesius 2015).

Given the significant differences in soil properties such as SOM content, pH, aggregation and infiltration rates often associated with contrasting tillage and cover cropping practices in similar soils (Blanco-Canqui et al. 2015; DeMaria et al. 1999; Mijangos et al. 2006; Poeplau et al. 2015; Poeplau and Don 2015; Stavi et al. 2016; Veenstra et al. 2006), there has been an expectation that microbial communities will reflect these variations by changes in community composition, diversity and function. Yet results from studies of the effects of different tillage regimes practices have reported mixed results. Some studies have reported large changes in diversity measures and community composition changes tentatively linked to reduced tillage (Dorr de Quadros et al. 2012; Souza et al. 2013; Souza et al. 2015; Wang et al. 2016), while contrasting studies have reported very minor to non-existent differences based on overall diversity matrices, as well as bacterial species composition (Degrune et al. 2016; Kaurin et al. 2015; Navarro-Noya et al. 2013). In addition, there is considerable functional redundancy in soil communities, and this can lead to a lower functional diversity observed in metagenomic studies (Souza et al. 2015), in comparison to phylogenetic diversity among taxa as determined by 16S rRNA gene sequencing (Souza et al. 2013). It should be noted that diversity matrices have been developed in macroorganism-occupied ecosystems with tens of species, where the disappearance or appearance of a few species can make a profound difference to ecosystem functioning. Similarly, each species in these systems can often be described adequately for its functional contribution to the ecosystem as a whole to be assessed. In the microbial community, with estimates of $>10^9$ individual organisms per gram of soil, hundreds to thousands of species, and rampant functional redundancy (Prosser 2012), these simple descriptive measures may not provide the right matrix to reflect the functional changes in the microbial ecosystem (Krause et al. 2014).

In addition, censuses of species or diversity measure alone do not lend themselves to useable conclusions that can translate microbial community differences into predictions as to how agricultural systems will respond to different challenges and perturbations. In this regard, assigning quantifiable ecologically important traits may be more important than metabolic function determination for individual species or groups of organisms. Estimating ecologically important trait values using 16S rRNA gene sequence-based phylogenetic placements could provide one way toward estimating microbial community-soil interactions, by describing communities in terms of the ecological types of taxa they contain. Community-wide estimation of microbial traits holds promise for ecologically-meaningful prediction of functional environmental change responses in a manner that allows more direct comparison across studies. The two most commonly utilized properties are 16S rRNA gene copy number and genome size (ref).

The Competitor-Ruderal-Stress tolerator life strategy scheme (C-R-S) designed for plants (Grime 1977), is likely to provide a good framework for linking these ecologically important traits to overall community function and predictions for community and soil characteristic evolution under different treatments. The C-R-S conceptual approach allows classification of groups employing mixed life strategies and offers more flexibility to accommodate the vast metabolic flexibility of bacteria, but the reliance of this approach on conservation of traits within phylogenetically coherent groups requires further experimental validation (Krause et al. 2014). In bacteria, the CRS approach has been successfully used to classify methane-oxidizing bacteria according their phylogenetic and functional properties (Ho et al. 2013).

The goal of this study was to characterize microbial community differences in soils under long-term conservation tillage and cover cropping practices, compare these to the *in-situ* physical and chemical soil characteristics, and use current bioinformatics tools to identify, analyze and provide functionally relevant interpretations of the observed patterns. To define relevant functional changes to the microbial communities we assigned estimate values for two ecologically-important traits: rRNA gene copy number (an indicator of maximum growth rate), and genome size (an indicator of metabolic diversity). We applied the observed trait scores to C-R-S conceptual approach in order to develop a functional framework for interpreting shifts in the microbial community.

Materials and Methods

Site Description

The 427 m by 100 m study site is located at the University of California’s West Side Research and Extension Center (WSREC - http://ucanr.edu/sites/westsiderec) in Five Points, CA (36°20′29″N, 120°7′14″W). The soils are Panoche clay loam (fine-loamy, mixed superlative, thermic Typic Haplocambids) (Arroues, 2006). Before the onset of the study (1998), a uniform barley (*Hordeum vulgare* L.) crop was grown and removed as green chop silage to reduce differences in soil water and fertility that may have existed due to previous research. At the time of this study, four tillage treatments were under study at the Research Center – conservation tillage (NOCT), conservation tillage plus cover

Treatment	**Plot numbers**			
CCCT	3	8	9	15
CCST	1	7	12	13
NOCT	4	5	10	16
NOST	2	6	11	14

crop (CCCT), standard tillage (NOST), and standard tillage plus cover crop (CCST) in a drip irrigated agricultural system consisting of alternate tomato/cotton rotation. Both rotation crops were grown simultaneously, one in each half of the experimental field. Each treatment was applied in four replicate plots arranged in a semi-randomized block system, for a total of 32 plots in total. The comparison of soil microbiology and chemical soil parameters reported here are restricted to the southern half of the conservation tillage research plots, specifically plots 1 -16 that were under tomato crop in 2013. Soil chemical and physical parameters available for analysis have been collected regularly in the fall from the beginning of the conservation project in 1999 to 2013 (Dhainaut Medina 2015; Mathesius 2015). The latest soil physicochemical data were used in statistical analyses with the microbial community data as determined by quantitative PCR (qPCR) and next Illumina sequencing in the fall of 2013.

Table 1. Treatments and plots sampled

Soil samples were collected from plots 1-16 on 11/22/2013. Twelve one-inch cores were collected from each of three depths (0-5, 5-15 and 15-30 cm) at each plot. The twelve samples from each plot/depth were homogenized and placed on ice in the field, then stored at -20°C before further analysis.

DNA extraction

Soil DNA was extracted in triplicate from 0.25 g (total humid weight) of soil using the Power Soil DNA Isolation Kit (MoBIO Laboratories, Carlsbad, CA, USA), according to the manufacturer’s instructions. DNA extraction was performed in triplicate for each soil sample. The quality and relative quantity of the extracted DNA was determined using a Qubit Fluorometer (Invitrogen, NJ, USA).

qPCR

The qPCR was performed on an Applied Biosystems (Applied Biosystems, NJ, USA) ABI 7300 sequence detection system using SYBR Green detection. The qPCR was performed in 20 µL reaction mixtures containing the following components: 10 µL of SYBR GreenER™ qPCR SuperMix (Invitrogen, NJ, USA), and 0.5 µM of each primer. Gene amplification was carried out with primer set 341F/534R for bacterial 16S rRNA gene (Lopez-Gutierrez et al. 2004; Muyzer et al. 1996; Muyzer et al. 1995), primers Arch771F/957R for Archaeal 16S rRNA gene (Ochsenreiter et al. 2003). A melting curve analysis was performed after each assay to ensure that only the products of the desired melting temperature were generated from the SYBR green qPCR. The R^2 values for the standard curves were 0.99 or better for all runs. All reactions were run in triplicate with a standard curve spanning 10^1–10^6 copy numbers for bacterial and archaeal 16S rRNA genes. The standard curves for quantifying gene copy numbers were determined by cloning the PCR products in a plasmid using the procedures reported by Okano et al. (2004). The population sizes of total bacteria and total archaea.

Sequencing

Amplification of the V4 hypervariable region of 16S rDNA was carried out using primer pair 515F (59-CACGGTCGKCGGCGCCATT-39) and 806R (59-GGACTACHVGGGTWTCTAAT-39) (Caporaso et al. 2012), modified by addition of Illumina adaptor and barcodes sequences (Lang et al. 2014). All primer sequences and a detailed PCR protocol are provided in Supplemental Table 4. Libraries were sequenced using an Illumina MiSeq system, generating 250bp paired-end amplicon reads. The amplicon data was multiplexed using dual barcode combinations for each sample.Amplicons were mixed at roughly equivalent ratios based on electrophoretic band intensity and purified using Agencourt Ampure XP magnetic bead purification kit (Beckman Coulter, CA, USA). Pooled samples were submitted to the University of California Davis Genome Center - 250-bp paired-end sequencing on the MiSeq platform.

Raw Illumina fastq files were demultiplexed, quality filtered (Q30), and analyzed using QIIME 1.8.8 pipeline and the GreenGenes 13.5 reference database. QIIME was used to assign Operational Taxonomic Units (OTUs) using UCLUST, with a threshold of 97% pairwise identity. Unweighted Unifrac distances were used to estimate Beta diversity.

Statistical Analysis

Data were analyzed using R statistical software package in RStudio version 0.99.446 (RStudio, Inc. 2015) with depth, tillage and cover cropping as random variables. The significance level for the variables and their interactions was set at 0.05. Prior to the analysis, assumptions of ANOVA were tested. Data for total bacteria and archaea were log transformed for analysis to meet the assumption of homogeneity of variance.

Results

Soil Chemical properties

There were three distinct patterns of changes in soil physicochemical properties: 1) pH, EC, P, NO_3^- exhibited some seasonal changes but overall no significant changes over time or differences between treatments were observed; 2) organic matter (OM) increased in all plots, but significantly higher increases were observed in cover crop (CC) treatments than no cover crop (NO) treatments irrespective of tillage: 3) total C and N showed no change while K showed slight decrease in the NO treatments, all three parameters showed a significant increase in the CC treatments (Mitchell et al, 2016).

Microbial population density

Bacteria had significantly higher total numbers at all depths under cover crops (Figure 1B.b), while under conservation tillage they had significantly higher numbers at 0-5 cm but lower numbers at 5-15 and 15-30 cm bgs compared to standard tillage Figure 1B.c). When the four combinations of treatments are compared with no consideration for depth, the pattern is less clear, although cover cropped treatments continue to show higher bacteria numbers under either conservation or standard till compared to the no cover crop treatments (Figure 1B.e). These results are consistent with the changes in SOM and N under different treatments and depths in the field. Archaea

Parameter	Bacteria P-value	Archaea P-value
Depth	3.78E-07	0.00965
Tillage	0.308	0.263
Cover Crop (CC)	0.00777	0.0169
Depth + Tillage	3.16E-07	0.0114
Depth + CC	5.25E-09	0.00381
Tillage + CC	0.0429	0.0718
Block	0.353	5.86E-06

showed similar trends to bacteria overall, but over a much smaller range (Figure 1B.b, d, f). Bacteria and archaea both showed greater total numbers at 0-5 cm and greater decrease in numbers with depth in the cover crop and conservation till treatments than in the respective standard treatments (Table 2). No significant difference was observed with tillage alone for either total bacteria or archaea. Overall, effect of treatment on bacteria was much stronger than on archaea (Table 2, Figure 1B). Archaea also showed a strong block effect, not evident with bacteria (Table 2). The reason for the strong block effect is not clear, as none of the chemical or physical characteristics or combinations of characteristics displayed similar effect.

Table 2. Anova for total numbers of bacteria, archaea, (AOA and AOB) for standard tillage and no-tillage systems, with and without cover crops at 0 –5, 5 - 15 and 15 – 30 cm depths in Five Points, CA

Total bacteria numbers were positively correlated with OM, P, K and total N and C; total archaea numbers were positively correlated with total bacteria numbers, P, K and total N and C (Table 3). In addition, total N and C positively correlated with OM, P, K and each other.

Figure 1A. qPCR analysis of in Mediterranean-climate agricultural soils under different cropping regimes: a) bacteria depth x CC; b) archaea depth x tillage; c) bacteria depth x tillage; d) archaea depth x tillage; e) bacteria CC x tillage; f) archaea CC x tillage. CCCT – cover crop, conservation tillage; CCST – covercrop, standard tillage; NOCT – no cover crop conservation tillage; NOST – no cover crop, standard tillage.

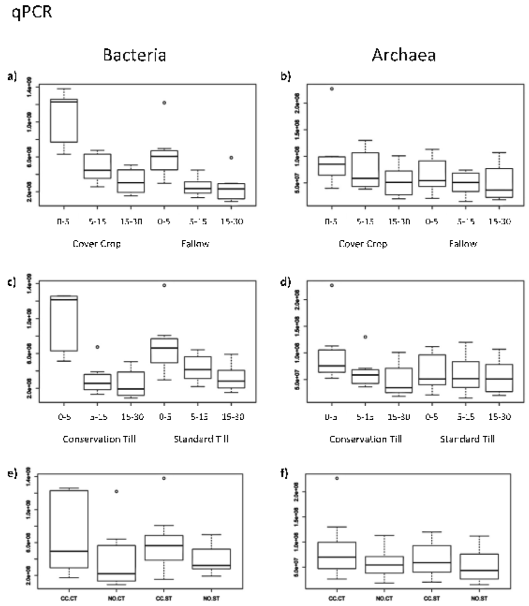
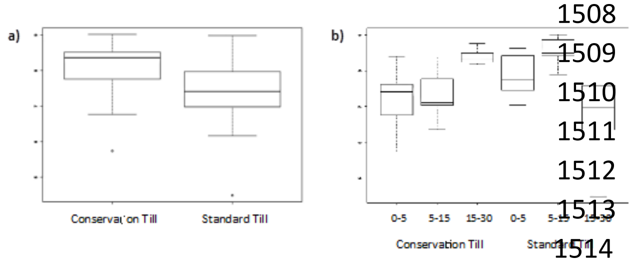


Figure 2. Differences in microbial community diversity in: a) different tillage treatments; b) different depths. (Shannon diversity index)

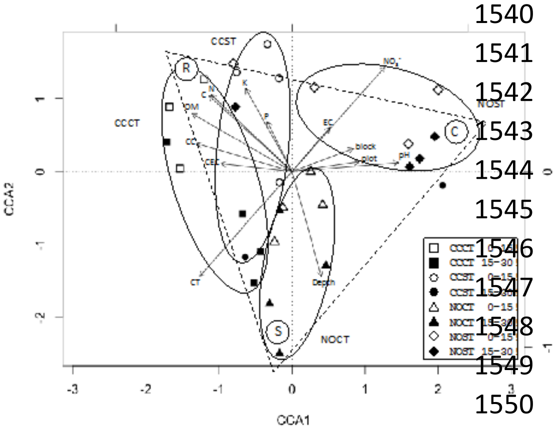


Microbial diversity

Whole community analysis showed the NOST treatment to be distinct from the other three treatments. Consistent with the qPCR analysis of highest total numbers, CC treatment soils showed highest species richness, while NO soils showed least richness. NOST treatments and NOCT at 0-5 cm showed similar trends in community composition and also clustered together in beta diversity analysis. Overall, the dominant phyla were *Actinobacteria* (27.2%), *Acidobacteria*

(12.8%), *Betaproteobacteria* (10.3%), *Chloroflexi* (8.7%), *Alphaproteobacteria* (8.0%) and *Planctomycetes* (7.6%). In the top 15 bacterial phyla (with *Proteobacteria* considered in their individual classes) the only group that showed a significant response to tillage were *Firmicutes*, their fraction increased under standard till (ST) treatments (Supplemental Table 2). *Alphaproteobacteria*, *Verrucomicrobia* and *Deltaproteobacteria* fractions increased with cover cropping, while *Firmicute* fractions increased in the absence of cover crops (Supplemental Table 2). *Alphaproteobacteria, Gammaproteobacteria, Bacteroidetes* and *Verrucomicrobia* fractions progressively decreased with depth, while *Chloroflexi*, *Deltaproteobacteria, Nitrospirae* and *WS3* fractions increased with depth (Supplemental Table 2).

Analysis of the microbial community diversity in various combinations of treatments showed significant differences only between treatments under conservation or standard tillage, and in combination of tillage and depth (Table 2). The Shannon diversity index was greatest under conservation tillage (Figure 2.a). Overall, diversity increased with increasing depth under conservation tillage, while it decreased with depth under standard till (Figure 2. b). The reason for the apparent increase in diversity with depth in the no till treatments is not clear.

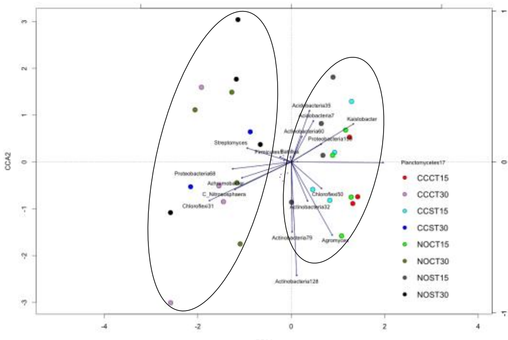


The four treatments separated bacteria at the genus level in a CCA constrained by soil physicochemical characteristics with the NOST furthest from the other three treatments along the primary axis (Figure 3). The two cover cropped treatments converged in the analysis at 0-15 cm bgs and separated from each other based on tillage status at 15-30 cm bgs. These treatments were associated with increased amounts of OM, C, N, P and K. The NOCT treatment separated from the other treatments along the secondary axis and was most associated with the effects of soil depth. Conservation tillage and NO_3^- concentration trended in opposite directions from each other. CCA analysis of physicochemical soil characteristics constrained by the most numerous bacterial genera showed that depth was the most important distinguishing feature separating all samples into two broad groupings along the primary axis (Figure 4).

Figure 3. Bacterial 16S rRNA sequence data. Canonical correlation analysis (CCA) of sequence data at the genus level constrained by soil physicochemical characteristics. C-R-S strategy pyramid superimposed on data.

Archaeal genera separated with depth and by cover crop treatment (Figure 5). There was relatively little evidence of tillage effects. Differences among management systems were greater at 15-30 cm depth than in the surface layer of soil. The treatment separation at the 0-15 cm depth followed the same trend as *Candidatus* Nitrosphaera (Figure 5).

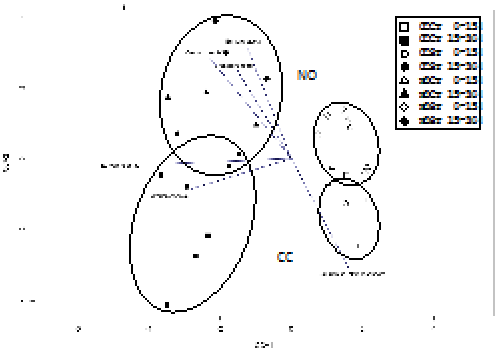
Figure 4. Bacterial 16S rRNA sequence data. Canonical correlation analysis (CCA) of the 17 most numerous taxa at the genus level correlated with soil physicochemical characteristics.



Soil depth is the most important characteristic for the most numerous taxa.

Members of this archaeal group are ammonium oxidizers that were found to predominate in farmed fields in a broad-reaching study of several systems comparing agricultural fields to nearby grasslands or woodlands at the Rothamsted Research station in the UK, and Kellogg Biological Station and Everglades Agricultural Area in the US (Zhalnina et al. 2013). *Ca.* Nitrososphaera increases correlated with increases in NH_3 (Zhalnina et al. 2013). While NH_3-N data were not available for this study, there was a 16% increase in total N in the CC treatment (Mitchell et al, 2016). The increase in *Ca.* Nitrososphaera numbers is consistent with increasing total N pool in the cover crop system.

Figure 5. Canonical correlation analysis (CCA) of archaeal 16S rRNA sequence data and soil physicochemical characteristics. CCCT – cover crop, conservation tillage; CCST – covercrop, standard tillage; NOCT – no cover crop conservation tillage; NOST – no cover crop, standard tillage; 15 - 0-15 cm depth interval; 30 - 15-30 dm bgs depth interval.

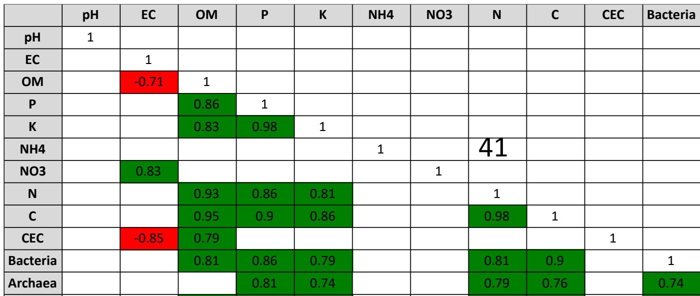


Functional trait analysis

Microbial communities in cover cropped soils showed a community wide decrease in rRNA copy numbers but an increase in genome size (Figure 6). Tillage, on the other hand, appeared to select for communities showing an overall decrease in both rRNA copy number and genome size. Gene copy number and genome size decreased with increasing depth in all systems. In combined cover cropping and tillage treatment analysis the NOST treatment showed the highest rRNA copy number estimate, with CCST second highest, and the two conservation till treatments showed similar copy numbers (Figure 7.a). Both tillage treatments showed a decrese in rRNA copy number estimate with depth, though the conservation tillage treatment showed significantly lower copy numbers at the lower depths than standard till (Figure 7.b).

Discussion

Bacteria and Archaea population densities positively correlated with indicators of SOM, including total C, N, P and K (Table 3). In addition, bacteria and archaea both showed significant response to cover cropping and conservation tillage, with increased numbers compared to the respective standard treatments (Table 2). The greater microbial



	pH	EC	OM	P	K	NH4	NO3	N	C	CEC	Bacteria
pH	1										
EC		1									
OM		-0.71	1								
P			0.86	1							
K			0.83	0.98	1						
NH4						1					
NO3		0.83					1				
N			0.93	0.86	0.81			1			
C			0.95	0.9	0.86			0.98	1		
CEC		-0.85	0.79							1	
Bacteria			0.81	0.86	0.79			0.81	0.9		1
Archaea				0.81	0.74			0.79	0.76		0.74

biomass at shallow depths could amplify even subtle differences in microbial communities between treatments. The relatively lesser overall decrease in archaeal density with depth under cover crop and conservation tillage treatments, in comparison to the steep decrease in bacteria numbers under the same treatments, may reflect the lower archaeal competitiveness with bacteria at the shallow depth on one hand, and better relative adaptability to nutrient limitation at greater depth on the other (Valentine 2007).

Table 3. Spearman correlation for chemical data with qPCR data. Significant correlations (P<0.05) highlighted in green (positive) or red (negative).

The effect of cover crops on microbial community composition likely depends on the cover crops or cover crop mixes used as has been shown in a study of three different single cover crops (Qin et al. 2016). Although Verrucomicrobia have been reported to increase with two of the three cover crops in the study of Qin et al (2016) and this study, that is the only group that has shown consistent increase between these studies. Groups that depend on specific microniches such as obligate anaerobes (e.g. firmicutes such as clostridia, methanotrophs) have been shown to be highly affected by aggregate disruption (Aslam et al. 2013; Dorr de Quadros et al. 2012). In the dry, aerobic soils in this study, there does not appear to be the same drive to increase anaerobic niches by reducing tillage as firmicute number increase rather than decrease with tillage, and it’s predominantly the bacilli, which are not obligate anaerobes, that represent the change. The ability to survive stresses such as tillage may be more important than dependence on specific microniches in these soils.

Table 5. Anova of functional traits rRNA gene copy number and genome size for standard tillage and no-tillage systems, with and without cover crops at 0 –5, 5 - 15 and 15 – 30 cm depths in Five Points, CA.

Parameter	**rRNA copy no.** **p-value**	**Genome Size** **p-value**
`CoverCrop`	0.0195	0.0326
`Tillage`	0.0021	0.1073
`Depth`	0.0025	0.0005
`CoverCrop:Tillage`	0.0305	0.3709
`CoverCrop:Depth`	0.338	0.4801
`Tillage:Depth`	0.1853	0.3543
`CoverCrop:Tillage:Depth`	0.5366	0.1375

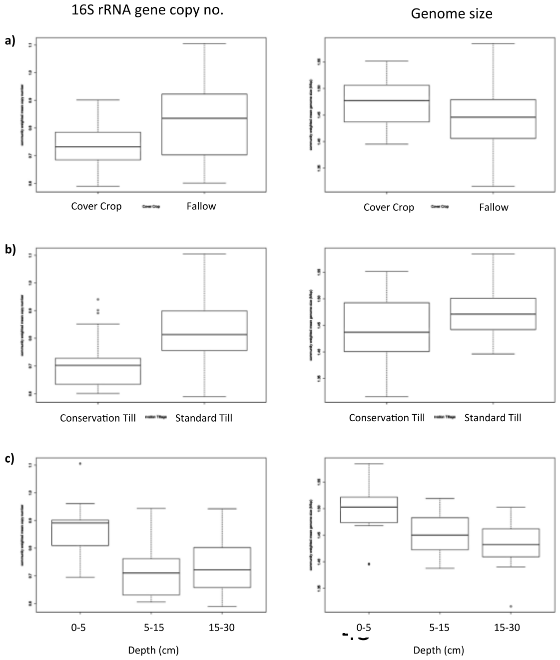
We applied the Competitor-Ruderal-Stress tolerator (CRS) life strategy framework (Krause et al. 2014) to the assigned trait estimates. Under the CRS framework More 16S rRNA gene copies suggest ability to more rapidly increase growth in response to increases in resources and also correlate with higher maximum growth rates (DeAngelis et al. 2015; Fierer et al. 2013; Green et al. 2008; Klappenbach et al. 2000; Krause et al. 2014; Lauro et al. 2009; Nemergut et al. 2015; Shrestha et al. 2007; Stevenson and Schmidt 2004; Vieira-Silva and Rocha 2010). Larger genomes suggest more metabolic and functional capabilities and, potentially, better adaptation to variable, heterogeneous environments. Smaller genomes correlate with greater specialization, but can be present in either rapidly growing competitors that maximize growth rates or slow growing stress tolerators that minimize resource use (Barberán et al. 2014; Fierer et al. 2013; Giovannoni et al. 2014; Guieysse and Wuertz 2012; Krause et al. 2014; Vieira-Silva and Rocha 2010).

Table 4. Anova of species richness estimates obtained at 3% genetic dissimilarity from Ilumina sequencing of 16S rRNA gene DNA for standard tillage and no-tillage systems, with and without cover crops at 0 –5, 5 - 15 and 15 – 30 cm depths in Five Points, CA.

Parameter	**Shannon** **P-value**	**Cho1** **P-value**	**Observed OTUs** **P-value**	**Whole Tree** **P-value**	**Adonis: unweighted** **P-value**
CoverCrop	0.6665	0.6685	0.478	0.351	0.0055
Tillage	0.0264	0.7381	0.3602	0.4802	0.0055
Depth	0.2879	0.5115	0.3062	0.2047	0.01
CoverCrop:Tillage	0.9653	0.6451	0.8645	0.9502	0.0126
CoverCrop:Depth	0.0689	0.9908	0.5285	0.5508	0.6849
Tillage:Depth	0.0051	0.0133	0.0119	0.0079	0.0093
CoverCrop:Tillage:Depth	0.3385	0.6024	0.3431	0.3098	0.1058

Based on our results cover cropping treatments aligned with ruderal strategies, standard tillage with competition strategies, while soil depth and conservation tillage aligned with stress tolerator strategies (Figure 8). We hypothesized that the NOST treatment microbial community enriched for competitors due to periodic availability of nutrients following tillage treatments, the CCST and CCCT treatments for ruderals because of the greater variety of carbon sources available due to cover crops, and the NOCT treatment for stress tolerators because these soils lacked both the cover crop inputs and periodic release of nutrients provided by tillage. The trends of microbial communities under the different treatments explained by the C-R-S concept were also consistent with the sample distribution in the genus-level CCA (Figure 4) both for the microbial communities and the physicochemical characteristics of the soils. It has been shown that disruption of soil aggregates by tillage releases physically protected organic materials, and thus enhances C mineralization (Elliott 1986; Six et al. 1999) and has been linked to the selection for copiotrophs (Carbonetto et al. 2014), that is organisms broadly equivalent to the competitors in the C-R-S model. Cover cropping appeared to mitigate both the lack of nutrient mixing in the no till treatment and periodic disruption of standard tillage, and resulted in the enrichment for ruderals – organisms with medium rates of growth and wider selections of metabolic capacities. Consistent with our findings, Jiao and coworkers (Jiao et al. 2013) have reported that a red clover cover crop selected for a wider range of metabolic capacities compared to non-cover cropped control in a soil microbial community.

Soil microbes are now considered important agents of SOM formation (Bradford et al. 2013; Miltner et al. 2012; Schmidt et al. 2011) because microbial-derived compounds are the primary constituents of stable, long-term SOM stores (Grandy and Neff 2008; Lundberg et al. 2001). As carbon inputs are assimilated and transformed by microbes into stable SOM (Bradford et al. 2013), the carbon use efficiency of the transformation pathway depends on ecological traits of the underlying microbial community (Sinsabaugh et al. 2016). By shifting the community away from competitors that maximize growth rates, the benefits are therefore likely to include higher capacity for carbon sequestration and reduced mineralization of both C and N. In addition, higher SOM correlates with better soil structure (Mitchell et al 2016), and the wider range of metabolic capacities



selected for by cover cropping may also play a role in greater adaptability and resistance to environmental stress (Schimel et al. 2007; Zak et al. 2003).

Figure 6. Phylogenetic estimation of ecologically important traits in Mediterranean-climate agricultural soils under different cropping regimes. Phylogenetic estimates were carried out for 16S rRNA gene copies per genome and genome size. The effects of a) cover cropping; b) tillage; c) depth. Soils samples were collected post harvest in fall 2013.

The use of cover crops in agriculture provide both potential advantages and disadvantages for the farmer. Cover crops increase soil organic C by 0.1–1 Mg ha^{-1} yr^{-1}, and decrease runoff, sediment loss and wind erosion (Blanco-Canqui et al. 2015; Poeplau et al. 2015; Poeplau and Don 2015). Their effects range from symbiotic nitrogen fixation by leguminous cover crops, physical root penetration of soil, and OM addition to increased soil surface protection by leaf and residue coverage (Blanco-Canqui et al. 2015; O'Connor 2015; Poeplau et al. 2015). Direct plant-carbon inputs of dissolved sugars, organic acids and amino acids to soil fuel heterotrophic microbial activity (Bradford et al. 2013), and this can have significant impact on soil structure; a recent experiment showed that removing plants from test plots for two years reduced soil aggregates by 22–33% (Blankinship et al. 2016). Consistent with these results, at Five Points, soil C in the cover crop treatments was 19.8% higher at 0-15 cm and 12.5% higher at 15-30 cm bgs when compared to the no cover crop treatments (Mitchell et al 2016). On the other hand, an important drawback of cover crops in water-limited regions is that they can reduce yields by reducing available water for the subsequent crops (Blanco-Canqui et al. 2015). Farmers need better tools to balance decisions on crop yield, resource use, and environmental services. By revealing the underlying trends of microbial community evolution under different treatment regimes, studies of cover crop effects on the soil microbial community such as the one presented here can therefore help provide critical information for better informed, rational farm management practice decisions.

The long term experiment at Five Points has already provided valuable information on the physical, chemical and crop effects of different tillage and cover cropping practices in seasonally dry Mediterranean soils (Dhainaut Medina 2015; Mathesius 2015) (Mitchell et al, 2016). This study describes the microbiological underpinnings of the soil fertility changes observed over the last 15 years of this experiment. Cover crops exert an important influence on microbial community composition as well as soil properties, with conservation tillage adding to the apparent benefits of cover cropping. In particular, the CCCT treatment consistently outperformed the other treatments in positive attributes including trends in OM, total C, total N, K total microbial numbers and microbial diversity. The enrichment of microbial communities in competitors, ruderals or stress tolerators explains the observed trends in measurable soil properties at Five Points, and provides a rationale for employing cover cropping and reduced till practices in order to enhance soil functions including carbon sequestration, stress tolerance and adaptability to environmental change.

Note that not all data from this work has been included in this report

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Cover cropping and no-tillage improve soil health in an arid irrigated cropping system in California's San Joaquin Valley, USA

Soil and Tillage Research In press

Abstract

The concept of soil health has attracted considerable attention during the past two decades, but few studies have focused on the effects on soil health of long-term soil management in arid irrigated environments. We investigated the effects of cover cropping and no-till management on soil physical and chemical properties during a 15-year experiment in California's San Joaquin Valley (SJV) USA. Our objective was to determine if soil health could be improved by these practices in an annual crop rotation. The impact of long-term no-tillage (NT) and cover cropping (CC) practices, alone and in combination, was measured and compared with standard tillage (ST) with and without cover crops (NO) in irrigated row crops after 15 years of management. Soil aggregation, rates of water infiltration, content of carbon, nitrogen, water extractable organic carbon (WEOC) and organic nitrogen (WEON), residue cover, and biological activity were all increased by NT and CC practices relative to STNO. However, effects varied by depth with NT increasing soil bulk density by 12% in the 0 – 15 cm depth and 10% in the 15 – 30 cm depth. Higher levels of WEOC were found in the CC surface (0 – 5cm) depth in both spring and fall samplings in 2014. Surface layer (0 – 15 cm) WEON was higher in the CC systems for both samplings. Tillage did not affect WEON in the spring, but WEON was increased in the NT surface soil layer in the fall. Sampling depth, CC, and tillage affected 1-day soil respiration and a soil health index assessment, however the effects were seasonal, with higher levels found in the fall sampling than in the spring. Both respiration and the soil health index were increased by CC with higher levels found in the 0 – 5 cm depth than in the 5 -15 and 15 – 30 cm depths. Results indicated that adoption of NT and CC in arid, irrigated cropping systems could benefit soil health by improving chemical, physical, and biological indicators of soil functions while maintaining similar crop yields as the ST system.

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Keywords

No-tillage, soil health, cover crops, arid regions, conservation agriculture

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1. Introduction

Soils are a finite natural resource that are nonrenewable under agricultural production without implementation of sustainable management practices (SSSA, 2015). Since the publication of '*Soil Quality, A Concept, Definition, and Framework for Evaluation (A Guest Editorial)*' by Karlen et al. (1997), and the pointed rebuttal, '*Reservations Regarding the Soil Quality Concept*,' by Sojka and Upchurch (1999), an energetic and at times acrimonious debate has been waged between proponents and critics of the concept of soil quality, or more recently, the related concept of soil health. Supporters point to the urgent needs, globally, to protect soils to ensure food security and ultimately human security (Wall and Six, 2015; Amundson et al., 2015). Skeptics argue, however, that relationships between soil attributes and how a given soil functions are poorly understood, that it is difficult to apply soil health practices broadly across diverse environments, and that the entire notion of soil health is abstract, particularly in regions like California where farmers achieve some of the highest crop yields, and yet soil quality assessments generally indicate low inherent quality (Andrews et al., 2002; Sojka and Upchurch, 1999).

Soil carbon (C) is one of the more important soil quality indicators that influence a variety of soil functions including nutrient and moisture retention (Hudson, 1994; Bettner, 2012). In California (Figure 1), intensive tillage, irrigation practices, and a hot, arid environment limit the potential to accumulate organic C in soil. Intensive irrigation practices over the past 60 years have led to an average increase of 1 to 1.3% soil C in agricultural soils, likely through the increases in crops yields and associated residue inputs as well as changes in the types and variety of crops grown (DeClerck and Singer 2003). Though challenging in hot, arid environments, increasing soil C above what can be gained through increased crop productivity due to irrigation practices can be achieved through increased crop residue inputs, particularly from cover crops (Clark et al., 1998; Mitchell et al., 2015). The benefits of cover crop (CC) practices include more productive soil, increased water use efficiency, reduced disease and pest pressure, and other ecosystem services (Follett, 2001; Alcantara et al., 2011; Ruiz-Colmenero et al., 2011; Schipanski et al., 2014).

Adoption of cover crops and no-tillage (NT) to increase soil quality and health has been difficult to promote in the California agricultural community (Mitchell et al., 2007; Mitchell et al., 2015). Crop yields in the state are on an ever-increasing trajectory due to sustained breeding and genetic improvement efforts, a number of parallel advances in production technology including particularly the adoption of precision micro-irrigation systems, giving little incentive to consider indicators of soil health (Mitchell et al., 2012; Phene, 2010). For example, tomato yields have increased by 50-80% with the adoption of subsurface drip irrigation (Hartz and Bottoms, 2009). Regardless of the demonstrated and perceived benefits of cover crops, the majority of growers do not adopt them due to costs of establishment and management, risk associated with timing of planting of cash crops, and other issues related to their compatibility with residue management and irrigation practices. Further, many people are concerned that practices currently endorsed to promote soil health are not relevant to the climate and crops of California because these practices were developed for rainfed, commodity crop farming systems with a winter fallow period and with typically higher soil organic matter (SOM) levels (Personal communication, T.K. Hartz). With the state's diverse base of high-value crops (CDFA, 2012) and given high yields achieved with existing management practices over the past century, there has been little incentive to explore or adopt soil health principles in California crop production. Furthermore, the value of the concept of soil quality or soil health in guiding soil research and conservation policy has been questioned (Sojka and Upchurch, 1999). If these practices are ever to be adopted, they need to be show value and also be achievable (Pannell et al., 2006).

Progress to identify general and unifying concepts linking specific agricultural management practices and soil function continues to advance (Ferris and Tuomisto, 2015) as does our ability to monitor and assess changes in soil health (SQI, 2001; Doran and Jones, 1996; Haney et al., 2008, 2010). Obade and Lal (2016), however, point out that "a universal model that quantifies soil quality remains elusive" because it cannot be directly measured and is only inferable by determining soil physical, chemical, and biological properties. Various minimum data sets (Franzluebbers, 2010) and measurement techniques (Obade and Lal (2016 have been proposed as means for achieving sensitive, easy to measure, and cost-effective indicators of soil health. Comparisons of these assessment tools with commonly-reported, traditional, volume-based assays of total soil C and N are needed (Franzluebbers, 2010). Over the past 20 years, a number of techniques or methods have been developed and used in a variety of formal assessments of various aspects of what was initially termed "soil quality," (Karlen et al., 1997), and is now generally defined as "soil health." Field monitoring procedures for water infiltration (Stamatiadis et al., 1999; Liebig et al., 1996), soil aggregate stability (Herrick et al., 2001), slaking (Seybold et al., 2002), and respiration (Liebig et al., 1996) were developed. Studies comparing these field tests to standard laboratory analyses have indicated that they have sufficient accuracy and precision to be of value in providing useful information (Liebiget al,, 1996; Herrick et al., 2001). Several of these field assessment tools have been combined by the USDA NRCS (2001) and have been used in a variety of evaluation context (Franco-Vizcaino, E. 1996; Parkin et al., 1996). Given that roughly 36 to 40% of our planet consists of arid lands and many of these soils support critical food production (White et al., 2009), it is particularly important to develop practices and assessment tools for improving soil function in these areas (Neary et al., 2002; Ladoni et al., 2010) and for providing reliable, inexpensive techniques for monitoring the performance of management efforts aimed at this goal.

The long-term University of California Conservation Agriculture (CA) Systems Project (UCCASP) was initiated in the fall of 1999 by a group of San Joaquin Valley (SJV) farmers, USDA Natural Resource Conservation Service (NRCS), private sector, and university partners to measure changes in soil and crop productivity with implementation of cover crops and NT in California's arid SJV. The original intent was to investigate farming practices that would reduce particulate matter emissions and increase soil C relative to the historically high soil disturbance practices that had been used in the region for over 80 years (Mitchell et al., 2015). At that time, NT practices were used on less than 2% of annual crop acreage in the SJV (Mitchell et al., 2007) and informal estimates indicated that the extent of cover cropping was at similar low levels of adoption. Results from the project demonstrated that cover crop inputs and reduced tillage resulted in much lower soil disturbance and increases in SOM (Mitchell et al., 2006, 2008, 2009; Veenstra et al., 2007). Various aspects and findings of the early stages of this long-term study including the ability of NT systems to increase soil C and N (Veenstra et al., 2006, 2007; Mitchell et al., 2009), reduce dust emissions (Baker et al., 2005) and production costs (Mitchell et al., 2009) and provide biomass to the soil via CC inputs (Mitchell et al., 2015) have been previously reported. Dust production was reduced by about 70% by the NT no cover crop (NO) treatment relative to the standard tillage (ST) NO system (Baker et al., 2005), soil C stocks increased with adoption of CC and NT (Mitchell et al., 2015), and computed values of the USDA Natural Resources Conservation Service (NRCS) soil conditioning index predicted SOM increases under NT and decreases under ST management (Mitchell et al., 2015).

The widespread adoption of subsurface drip irrigation in California over the past decade has increased the feasibility of adoption of reduced tillage systems because there is less need to disturb soil compared to surface irrigation systems. Because of these increased opportunities, it is especially important to evaluate and possibly modify indicators of soil health in irrigated, arid agricultural systems such as found in the SJV. Our objectives were to measure changes in soil properties and processes to provide a framework for assessing indicators of soil health in a long-term tomato (*Solanum lycopersicum* L.)-cotton (*Gossypium hirsutum* L.) rotation study (1999 to 2014) measuring different tillage (standard and no-tillage) and cover crop (with and without) systems. We hypothesized that long-term cover cropping and NT would result in changes in soil health as measured by a variety of recently-introduced soil physical, chemical and biological assays.

2. Methods

2.1 Site

The study site is located at the University of California's West Side Research and Extension Center (WSREC) in Five Points, CA (36°20′29″N, 120°7′14″W). Soils are Panoche clay loam (fine-loamy, mixed superlative, thermic Typic Haplocambids) (Arroues, 2006). Average monthly maximum and minimum temperatures are provided in Table 1.

Table 1. Thirty-year average monthly maximum and minimum temperatures (^{0}C) for Five Points, CA

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
average maximum temperatures	13.4	17.3	20.9	24.3	29.5	33.1	35.5	34.9	32.1	26,7	18.7	13.3

average minimum temperatures	3.9	5.2	6.8	8.8	12.2	14.8	17.2	16.8	14.8	10.6	5.9	3.3

In 1998 before the study began, a uniform barley (*Hordeum vulgare* L.) crop was grown and removed as green chop silage to even out differences in soil water and fertility that may have existed due to previous research.

2.2 Cropping systems descriptions

The 3.56 ha field consisted of 32 plots each 10-m wide by 100 m long with 10-m buffer or border plots between treatment plots (Baker et al., 2005). A tomato-cotton rotation was planted in one half, and a cotton-tomato rotation in the other half so that both entry points were represented each year from 2000 to 2013. To better achieve the conservation agriculture goal of crop rotation diversity (Mitchell et al., 2015), the systems were changed to sorghum (*Sorghum bicolor*) and garbanzo beans (*Cicer arietinum*) in 2014 (Mitchell et al., 2016). Management treatments included a factorial arrangement of tillage and CC, including standard tillage without cover crop (STNO), standard tillage with cover crop (STCC), no-tillage without cover crop (NTNO), and no-tillage with cover crop (NTCC). Each treatment was replicated four times in a randomized complete block design in each half of the field. Treatment plots consisted of six beds, each measuring 9.1 x 82.3 m. Six-bed buffer areas separated tillage treatments to enable the different tractor operations that were used in each system. Both the ST and the NT systems were previously described in detail (Veenstra et al., 2006; Mitchell et al., 2015) and in summary consisted of conventional intercrop tillage operations of residue shredding, multiple diskings to incorporate residues to a depth of 20 cm, use of a subsoiling shank before the tomato and cotton crops to a depth of about 30 - 45 cm, additional disking to 20 cm to break up soil clods created by the subsoiling shank following tomatoes, listing of beds, and power incorporation of the surface 10 cm of soil using a cultimulcher (BW Implement, Buttonwillow, CA) which is a PTO (power take off)-powered aggressive tillage operation that pulverizes the surface 20 cm of soil creating a fine, powdery seed bed for both the STNO and the STCC systems. Conventional intercrop tillage practices that break down and establish new beds following harvest were used in the CT systems. The NT systems were managed from the general principle of trying to reduce primary intercrop tillage to the greatest extent possible. Controlled traffic farming, or zone production practices that restrict tractor traffic to certain furrows were used in the NT systems, and planting beds were not moved or destroyed in these systems during the entire study period. Following this series of tillage operations that were used in the ST systems, percent surface residue amounts averaged typically over 90 for the NTCC, between 40 and 70 for the NTNO, between 10 and 20 for the STCC, and below 5 for the STNO (Mitchell et al., 2015). The only soil disturbance operations used in the NT systems were shallow cultivation during the first eight years for the tomato crops. As the project progressed, the NT treatments became true no-tillage systems in 2012 with the only soil disturbance occurring at the time of seeding or transplanting. While there was some shallow weed cultivation disturbance during the early years of the study, we believe that the term “no-tillage” most aptly characterizes this tillage system and is a better descriptor than any of the alternatives such as “reduced,” “minimum,” or “conservation tillage” that have been used (Reicosky, 2015, Mitchell et al., 2012).

In the tomato-planted half of the field, a common commercial variety in the SJV, ‘8892,’ was transplanted in the center of beds at an in-row spacing of 30.5 cm and a final population of 21,581 plants ha^{-1} during the first week of April in each year using a modified three-row commercial transplanter fitted with a large (50 cm) coulter ahead of each transplanter shoe. Treatments received the same fertilizer applications with dry fertilizer (11-52-0 NPK) applied preplant at 89.2 kg ha^{-1} (9.8 kg ha^{-1} N and 46.4 kg ha^{-1} P) using a standard straight fertilizer shank at about 15 cm below the transplants. Additional N (urea) was side dress applied at 111.5 kg ha^{-1} for a total of 51.3 kg N ha^{-1} in two lines about 18 cm from the transplants and about 15 cm deep about four weeks after transplanting.

The RoundUp Ready™ transgenic upland cotton variety ‘*Riata*’ was used from 2000 - 2007 in all cotton systems and was established using a John Deere (Moline, IL) 1730 No-till Planter. In 2008 and 2009, an experimental RoundUp Ready Flex™ Pima variety, ‘Phy-8212 RF, ‘was grown. Approximate plant populations in all years were 148,000 ha^{-1}. Dry preplant fertilizer (11-52-0) was applied at 224 kg ha^{-1} using shanks at about 20 cm depth and then mixed throughout the ST beds using bed preparation tillage implements and shanked in the NT systems.

The tomato and cotton crops were furrow irrigated from 2000 – 2012. In keeping with trends in the region toward more efficient systems, however, the study site was converted to subsurface drip irrigation in 2013 with 34 mm diameter tape buried 30 cm in the centers of each 150 cm-wide planting bed. Installation of the drip tape at this time constituted a tillage operation to all systems. The basic equation

$$ETc = Kc \cdot ETo$$

where, ETc is the projected evapotranspiration of the tomato crop, Kc is a corresponding growth-stage dependent crop coefficient, and ETo is reference evapotranspiration for a given production region (Hanson and May, 2005, 2006) was used to schedule furrow irrigations of both crops throughout the study. ETo data were acquired from a California Irrigation Management Information System (CIMIS) (http://wwwcimis.water.ca.gov/cimis/welcome.jsp) weather station located about 200 m from the study field. Crop coefficient (Kc) values were based on crop canopy estimates for each irrigation plot. Applied water amounts averaged about 71 cm ha^{-1} for tomato and 61 cm ha^{-1} for cotton, which are close to historical estimates for ETc and commercial application volumes in the region (Hanson and May, 2006).

A CC mix of Juan triticale (*Triticosecale* Wittm.), Merced rye (*Secale cereale* L.) and common vetch (*Vicia sativa* L.) was seeded using either a 5-m John Deere 1530 no-tillage single-disc opener seeder (Moline, IL) or a 5-m Sunflower 1510 double-disc opener no-till drill (Beloit, KS) at 19 cm row spacing and at a rate of 89.2 kg ha^{-1} (30% triticale, 30% rye and 40% vetch by weight) in late October in the STCC and NTCC plots and irrigated once with 10 cm of water in 1999 and again with 5 cm in 2012 and 5 cm in 2014. The legume species was inoculated with rhizobium before seeding. In each of the subsequent years through 2012, no irrigation was applied to the cover crops, which were planted in advance of winter rains. Between 2010 and

2014, the basic CC mixture was changed to include a greater diversity of species including pea (*Pisum sativum* L.), faba bean (*Vicia faba* l.), radish (*Raphanus sativus*), and Phacelia (*Phacelia tanacetifoli*) (Mitchell et al., 2015). Cover crop biomass was determined in mid-March of each year of the study by harvesting all aboveground plant material in a 1 m^2 (11 ft^2) random area in each plot, drying the material to constant weight, and weighing (Mitchell et al., 2015). Percent surface residue was determined using the line-transect method on April 20, 2004, December 18, 2009, and August 10, 2014 (Bunter, 1990).

2.3 Soil and Plant Analysis

Soils were sampled in 1999 and 2014 at two depths (0 to 15 cm and 15 to 30 cm) in the fall after harvest. In each plot, six to eight 7.6-cm-diameter cores per depth were composited before air drying, sieving through a 2 mm sieve and grinding using a soil pulverizer to pass through a 60 mesh screen, and dried to constant weight according to protocols of the University of California, Davis Analytical Laboratory (http://anlab.ucdavis.edu/sampling/soil-sampling-and-preparation). Total C and total N were measured using a combustion C analyzer (CE Elantech, Inc., Lakewood, NJ). Bulk density was measured by the compliant cavity method (USDA NRCS, 2004) for the two depths in 2014. To calculate total C and N in 1999, the bulk density (BD) that had been measured for STNO treatment in 2003 was taken and it was assumed that all plots at this time, before the start of the experiment, were the same. Surface soil water stable aggregate percentages, slaking, and water infiltration were determined in 2012 using USDA NRCS Soil Quality Test Kit procedures (USDA, 2001) with eight, ten, and four subsamples per plot for each of these assays, respectively (Soil Quality Institute, 2001). Soil water infiltration was determined using a single ring (15 cm diameter) inserted into the soil to a depth of 7.5 cm. A volume (400 ml) equivalent to 2.54 cm of water was applied to the surface soil in the ring and the time required for infiltration, which was determined as the time taken for standing water to enter the soil, was recorded. Four replicate measurements were made in each treatment plot. Aggregation was determined by gradually wetting and subsequent immersing of a known weight of 2 mm soil aggregates followed by reweighing, dispersal using sodium hexametaphosphate, and a final reweighing. Slaking was assessed by visually determining the stability of soil aggregates exposed to rapid wetting using 1.5 cm diameter sieves. In spring and fall of 2014, soil samples at 0 – 5 cm, 5 – 15 cm, and 15 – 30 cm depths were collected to determine water extractable organic C (WEOC) and water extractable organic N (WEON) and 1-day CO_2-C respiration using procedures developed as part of the Soil Health Index (SHI) (Haney, 2015). These values are then used to calculate a soil health index according to:

$$\mathrm{SHI} = \frac{1 - \mathrm{day\ CO_2 - C}}{\mathrm{C{:}\,N} + \ (\mathrm{WEOC} - 100 + \mathrm{WEON} - 10)}$$

(Haney, 2015). Throughout the entire long-term study, soils were consistently sampled in the fall, typically following postharvest tillage operations (Mitchell et al., 2015), however, we also added a spring sampling in 2014 in an effort to compare data during the spring when soil water contents are higher than they are in the fall.

In fall 1999, soil C, N, pH, electrical conductivity (EC), K, and P (Dhainaut, 2015) and texture (Baker et al., 2005) were measured. Results indicated that the study field was relatively uniform with respect to these properties except texture (Baker et al., 2005). Soil particle size analysis showed a distinct texture gradient from south to north across the field. Textures varied from clay loam (32% clay, 33% silt, 35% sand) at the south end (13m) to sandy clay loam (23%, clay, 23% silt, 54% sand) at the north end (360 m). Although the soil is mapped as Panoche clay loam, our data indicated a variation from the named soil phase within the field and demonstrate the natural variability inherent in soils at this level of mapping. We do not have baseline data for infiltration or aggregate stability; however, based on the uniformity of cropping patterns and the ST management across the field for decades prior to our experiment, we believe that pre-existing differences in these processes across our test plots were minimal.

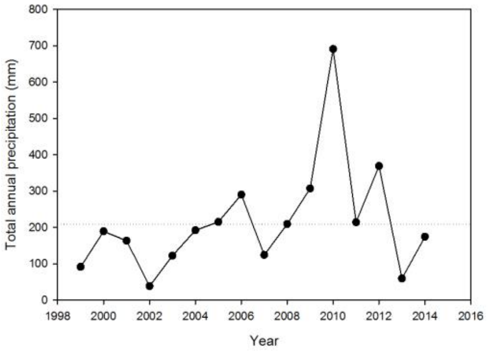
2.4 Statistical Analysis

Data were analyzed using PROC Mixed procedures with tillage and CC as fixed variables and years and replication as random variables using SAS statistical software (SAS Institute, 2002). Year was considered a random variable as the crops were rotated between the two experimental blocks each year. Interactions between years and the factors were also tested. Whenever there was a significant interaction between years and the factors, data were separated by years and re-analyzed. The significance level for the variables and their interactions was set at 0.05. Prior to the analysis, assumptions of ANOVA were tested. Data for total C and total N were log transformed for analysis to meet the assumption of homogeneity of variance. Whenever ANOVA showed significant differences ($P<0.05$), means were separated using either Fisher’s Protected Least Significant Difference method or the pdiff option in SAS. Mean separation was based on transformed data, but non-transformed means were presented for clarity.

3. Results and Discussion

3.1 Cover crop biomass

Over the 15 years of the project that was characterized by recurring drought (Figure 2), a total of 56 t ha^{-1} of aboveground CC biomass representing 1,196 kg ha^{-1} of N and 21,722 kg ha^{-1} of C was produced with a total precipitation of 344 cm and 20 cm of supplemental irrigation applied in 1999, 2012, and 2014 (plus residual soil moisture following summer crops which is assumed to have been negligible). Cover crop biomass varied from 39 kg ha^{-1} in the low precipitation period (winter 2006 – 2007) to 9,346 kg ha^{-1} (winter 2000 – 2001) (Mitchell et al., 2015). Cover crop aboveground biomass was similar between tillage treatments (Mitchell et al., 2015), but tended to be higher following tomato than following



cotton (Mitchell et al., 2015) presumably due to the higher residual soil N that may have been present following tomato.

3.2 Soil physical health indicators

Both CC and tillage impacted the infiltration of both the first and second 400 ml (equivalent to 2.54 cm) of applied water with faster infiltration occurring in the NT and CC systems (Table 2). The fastest infiltration rates were observed in NTCC (Table 2). When treatments were isolated, means for CC infiltration times for the first 2.54 cm of applied water were 2.8 times more rapid than with no CC (0.71 minutes CC, 1.46 minutes NO) whereas tillage produced a two-fold difference in favor of NT treatments (0.57 minutes NT, 1.6 ST). For the second 2.54 cm of applied water, CC infiltration times were 2.2 times more rapid than no CC (4.02 minutes CC, 8.69 minutes NO), and infiltration under NT was 1.4 times more rapid than under ST (5.38 minutes NT, 7.33 minutes ST).

Differences in sustained infiltration between NT and ST may have resulted from increased slaking associated with ST that could have clogged soil pores and contributed to slower infiltration rates. Slower infiltration of the second 400 ml in the NTNO treatment may have resulted from the higher soil BD of this system (Table 2). Increased infiltration rates in NT soils observed in other studies were attributed to formation of macropores, often caused by earthworms (Edwards et al., 1988), as well as to the continuity of soil pores throughout several horizons in the profile (Ehlers, 1975; Barnes and Ellis, 1979; Beisecker, 1994; Hangen et al., 2002). Increased aggregate stability under NT ensures that aggregates are less likely to slake and clog pores. Tillage disrupts pore continuity and destroys large aggregates, thereby increasing the likelihood of particle slaking and pore clogging, resulting in lower infiltration rates.

Table 2. Determinations of soil water infiltration, slaking, and water stable aggregates using the USDA NRCS Soil Quality Test Kit for standard tillage (ST), no-tillage (NT), with cover crop (CC) and without cover crops (NO) in Five Points, CA

Source of variation	Infiltration 1st 400 ml*	Infiltration 2nd 400 ml	Slaking after 5 min	Slaking† after 5 dips	Water stable aggregates
	(min)	(min)			(%)
Tillage					
ST	1.46 a††	7.33 a	2.13 b	3.89 b	50
NT	0.71 b	5.38 b	2.70 a	5.01 a	51
Cover crop					
CC	0.57 b	4.02 b	2.62 a	5.09 a	57 a
NO	1.60 a	8.69 a	2.20 b	3.81 b	44 b

STNO	2.07	8.29	1.94	3.19	41
STCC	0.86	6.37	2.31	4.59	58
NTNO	1.13	9.10 A[°]	2.47	4.44	46
NTCC	0.28	1.67 B	2.92	4.58	57
P-values					
Tillage	0.0030	0.0036	<0.0001	<0.0001	0.9313
Cover crop	0.0036	0.0007	0.0023	<0.0001	<0.0001
Tillage*Cover crop	0.6785	0.0109	0.8177	0.7940	0.4621

[*] Soil water infiltration determined using 15 cm diameter ring with a measured area of 176.9 cm^2

[†] Soil stability class visual ratings (1-6, with indicating greater stability) using the USDA NRCS Soil Quality Test Kit (2001).

[††] For tillage and cover crop systems main effect, means followed by the same lowercase letters within columns are not significantly different according to LSD (0.05).

[°] For the 2nd 400 ml infiltration, significant difference occurred between the NTNO and NTCC treatments but not between STNO and STCC treatments as denoted by the uppercase letters based on LSD (0.05) test.

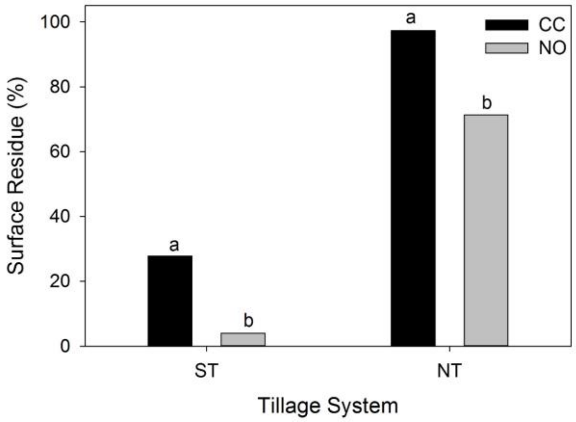
The faster initial infiltration rates observed under CC may result from development of root channels, and the absence of tillage under NT probably helps maintain these channels as relatively continuous macro- and micropores. This, in addition to a lack of disturbance of earthworm tunnels, would explain why infiltration rates were most rapid in NTCC than in the other treatments. Our prior work with NTCC systems (Herrero et al., 2001), as well as unpublished recent measurements in the UCCASP field have documented higher earthworm populations in surface NTCC soils than in STNO soils.

The NRCS Soil Quality Test Kit used in this study contains two protocols, the slake test and the aggregate stability test, that provide indications of soil stability (SQI, 2001) for surface soil layers. Both tillage and cover crops decreased slaking, a determination that is based on a visual assessment of the stability or structural integrity of soil fragments (~ 1.25 cm in diameter) upon rapid wetting (Table 1). These relative differences among treatments seen in the slake test contrasted with results from the stable aggregate measurements. For water stable aggregates, CC was the dominant factor driving treatment differences, while the larger aggregates used in the slake test are influenced by CC, as well as tillage (Table 2). Tisdall and Oades (1982) categorized aggregate binding agents as transient (polysaccharides), temporary (roots and fungal hyphae) and persistent (resistant aromatic compounds associated with polyvalent cations). Cover crop treatments may have some advantage in generating aggregate stability due to the continuous supply of C to fungi and polysaccharide-producing bacteria throughout the year (Le Guillou et al., 2012). The larger macroaggregates as measured in the slake test are affected by CC and tillage. Tillage affects both macro- and microaggregates. The reduced rate of macroaggregate turnover under NT practices has been shown to lead to the formation of stable microaggregates in which C is sequestered and stabilized in the long term (Six et al., 2000; Six and Paustian, 2014).

While the stationary submersion slake test provides an indication of soil strength, the repeated submersions slake test and water stable aggregates test measure the integrity of soil when water flows across the surface and through pores. In these tests, and under more intense precipitation, aggregates that break apart as water flows over them and through the pore space are more likely to clog pores (Helalia et al., 1988), reducing the overall continuity of pores and impeding downward infiltration. Micro and macro-aggregate stability measurements are thus indicative of the tendency of a soil to break apart into smaller particles and cause clogging or crusting, thereby affecting water infiltration rates. In addition, although not measured in this study, we have observed evidence of earthworms and associated holes in the CC and NT systems which may have also contributed to the more rapid water infiltration in these systems (Herrero et al., 2001; Mitchell et al., 2015;).

3.2 Surface residue

Percent residue cover for the August 10, 2014 sampling is shown in Figure 3. Averaged over the three sampling times, percent residue cover was 4 (STNO), 14.7 (STCC), 67.3 (NTNO), and 92 (NTCC). In regions of the world where NT systems are common — such as Brazil, Argentina, Paraguay, Canada, Western Australia, the Dakotas and Nebraska — generating and preserving residues are an indispensable part of management and major, even primary, goals of sustainable production and of conservation agriculture systems (Dumanski et al., 2006; Crovetto, 1996, 2006). Residues can reduce erosion (Shelton et al., 2000a and b; Skidmore 1986), provide C and N to soil organisms (Crovetto 2006) and reduce soil water evaporation (Klocke et al. 2009; van Donk et al. 2010), and lower soil temperatures (Mitchell et al., 2012). Potential drawbacks of residues, however, may include difficulties with crop seeding, their harboring of seedling pests, and rodents, all of which may be serious particularly for high value vegetable crops in terms of food safety concerns.



3.3 Soil carbon, nitrogen and bulk density

Data were analyzed separately for each depth because of an interaction between depth and tillage for the variables. Year, tillage, and CC had an effect on total C and total N. However, these effects were only significant in the 0 to 15 cm for BD (Table 3). There was no interaction between year and the other variables for total C, total N and BD; therefore, data were combined for the years and analyzed. Total C and total N was greater in 2014 than in 2012 at both soil depths (Table 3). Total C was approximately 53% and 22% greater in the NT than in the ST system in the 0-15 cm and 15-30 cm depth, respectively. Total N was also 47% and 15% greater in the NT than in the ST system in the 0-15 cm and 15-30 cm depth, respectively. Similarly, BD was 8% and 15% greater in the NT than in the ST system in the 0-15 cm and 15-30 cm depth, respectively. Total C and total N was also increased by the inclusion of cover crops at both soil depths regardless of tillage system. For example, total C was 20% and 13% greater in the CC than in the NO system in the 0-15 cm and 15-30 cm depth, respectively. Total N was 12% and 10% greater in the CC than in the NO system in the 0-15 cm and 15-30 cm depth, respectively. Soil BD, however, was greater in the plots with no cover crops at the 0-15 cm depth but this difference did not occur at the 15-30 cm depth (Table 3). Therefore, these results showed that NT resulted in greater total C and N than the ST system, regardless of the presence of a CC; whereas, CC increased total C and N regardless of the tillage system. Other studies conducted in arid and semi-arid regions under irrigation (Munoz et al., 2007; Kong et al., 2005) have shown similar increases in soil C with cumulative C inputs. Kong et al. (2005) reported a direct relation between soil C stabilization and aggregation with C inputs from crop residue and added C amendments. Munoz et al. (2007) similarly showed increases in C, N, aggregate stability, water content, and total culturable microorganisms with direct seeding and direct seeding with winter cover crops.

Table 3 Soil carbon (C), nitrogen (N), and bulk density for standard tillage (ST) and no-tillage (NT) systems with (CC) and without (NO) cover crops at 0 – 15 cm and 15 – 30 cm depths (combined for fall 2012 and 2014) in Five Points, CA

Source of variation	Total C	Total N	Soil bulk density
	g cm^{-3}	g cm^{-3}	g cm^{-3}
Soil depth (0 – 15 cm)			
Year			
2012	16.43 b†	1.84 b	1.13 b
2014	22.53 a	2.48 a	1.18 a
Tillage			
ST	15.42 b‡	1.75 b	1.11 b
NT	23.55 a	2.57 a	1.20 a
Cover crop			
CC	21.24 a‡	2.32 a	1.13 b
NO	17.73 b	2.00 b	1.18 a
STNO	13.90	1.61	1.13
STCC	16.95	1.90	1.09
NTNO	21.56	2.39	1.24
NTCC	25.53	2.75	1.17

ANOVA			
		P-value	
Year	<0.0001	<0.0001	0.0350
Tillage	<0.0001	<0.0001	0.0001
Cover crop	0.0017	0.0026	0.0191
Year X tillage	0.6592	0.5107	0.8519
Year X cover crop	0.9200	0.9649	0.3052
Tillage x cover crop	0.0579	0.6491	0.3839
Year X tillage X cover crop	0.9005	0.7397	0.4871
Soil depth (15 – 30 cm)			
Year			
2012	13.83 b†	1.71 b	1.45
2014	16.92 a	2.05 a	1.45
Tillage			
ST	14.43 b‡	1.75 b	1.35 b
NT	16.33 a	2.01 a	1.55 a
Cover crop			
CC	16.28 a‡	1.97 a	1.45
NO	14.47 b	1.79 b	1.45
STNO	13.23	1.64	1.36
STCC	15.62	1.87	1.35
NTNO	15.72	1.94	1.55
NTCC	13.23	2.08	1.55
ANOVA			
		P-value	
Year	<0.0001	<0.0001	0.8408
Tillage	0.0026	<0.0001	<0.0001
Cover crop	0.0038	0.0041	0.8505
Year X tillage	0.9644	0.6672	0.0594
Year X cover crop	0.6408	0.9461	0.5014
Tillage x cover crop	0.1825	0.2823	0.8192
Year X tillage X cover crop	0.7167	0.7238	0.3028

3.4 Soil Health Assessment Index

Soil depth was a significant factor for each determination in both the 2014 spring and fall SHI samplings with generally higher values for each assay associated with shallower soil depth (Tables 4). This enrichment of nutrients, organic matter, and biological activity in surface layers in soils transitioning to no-till and high residue conditions as in the NT systems and in particular, in the NTCC systems, is quite common (Crovetto, 1996, 2006; Franzluebbers, 2002). In the CC systems, respiration, water extractable organic C and N, and the overall SHI were higher than in the other treatments. Both spring and fall respiration (1-day CO_2 evolution) was sorted by depth and then analyzed further because of interactions that occurred within both datasets (Tables 5a and b). In the top (0 – 5 cm) depth, higher 1-day CO_2 evolution values were found in the CC systems in the spring most likely due to an actively growing root which would add an easily mineralizable C source upon which the microbial biomass could feed, and with both the CC and NT in the fall due to increased temperature from the summer months. Cover crop raised respiration in both the 5 – 15 cm and the 15 – 30 cm depths in both spring and fall. Soil WEOC was highest in the NT systems. Since WEOC is a subset of the SOM, it follows that WEOC is higher in the NT system as is total C. However, WEOC is likely a more precise measurement of the immediate potential activity of the soil microbes since WEOC is the C pool that is readily acted upon by the soil microbes.

Table 4. Analysis of variance table for Soil Health Tool determinations of 1-day respiration, water extractable organic carbon, water extractable organic nitrogen, the ratio of water extractable carbon to nitrogen, and the soil health calculation for standard tillage (ST), no-tillage (NT), with (CC) and without (NO) cover crops at 0-5 cm, 5-15 cm, and 15-30 cm soil depths in Five Points, CA in the spring and fall of 2014.

Source of variation	1-day CO_2-C	Organic C	Organic N	Organic C:N	Soil Health Calculation
			P-values		
Spring 2014					
Tillage	0.9082	0.0155	0.8157	0.0510	0.0781
Cover crop	<0.0001	<0.0001	<0.0001	0.0002	<0.0001
Depth	<0.0001	<0.0001	<0.0001	0.0702	<0.0001
Tillage x cover crop	0.7040	0.3405	0.0317	0.0128	0.0456
Tillage x depth	0.0909	0.0009	0.4475	0.3655	0.1859
Cover crop x depth	<0.0001	0.0024	0.0294	0.7946	<0.0001
Tillage x cover crop x depth	0.0989	0.8405	0.6011	0.2528	0.6056
Fall 2014					
Tillage	<0.0001	<0.0001	<0.0001	0.0077	<0.0001
Cover crop	<0.0001	<0.0001	<0.0001	0.1473	<0.0001
Depth	<0.0001	<0.0001	<0.0001	<0.0001	<0.0001
Tillage x cover crop	<0.0001	0.0024	0.0009	0.0492	<0.0001
Tillage x depth	<0.0001	<0.0001	<0.0001	0.0095	<0.0001
Cover crop x depth	<0.0001	<0.0001	0.0001	0.5972	<0.0001
Tillage x cover crop x depth	<0.0001	0.0011	0.0101	0.4049	<0.0001

In the fall, both CC and NT resulted in higher surface (0 – 5 cm) WEOC again due to the higher summer temperatures, but in the spring, only the presence of CC led to higher WEOC in the shallow, 0 – 5 cm depth with active roots providing the enhanced C values. For the 5 – 15 cm depth, CC systems were again higher than the no CC systems for both samplings, but in the spring, ST systems had slightly higher WEOC levels than the NT systems, though an opposite trend surfaced in the fall. At the 15 – 30 cm depth, CC resulted in higher WEOC levels in both the spring and fall samplings with the ST system having higher levels at this depth in the spring only.

Table 5a. Soil Health Tool determinations of 1-day respiration water extractable organic carbon, water extractable organic nitrogen, the ratio of water extractable carbon to nitrogen, and the soil health calculation for standard tillage (ST), no-tillage (NT), with (CC) and without (NO) cover crops in Five Points, CA in the spring of 2014.

Source of variation	1-day CO_2-C	Organic C	Organic N	Organic C:N	Soil Health Calculation
	ppm	ppm	ppm		
Soil depth (0 – 5 cm)	31.9	267.2	21.2	14.7	8.0
Tillage					
ST	23.4†	253.5	20.4	14.6	6.9
NT	40.4	280.9	21.9	14.8	9.0
Cover crop					
CC	51.7 a‡	337.8 a	28.5 a	13.7	11.4 a
NO	12.2 b	196.5 b	13.8 b	15.7	4.6 b
STNO	11.6	187.8	12.0	18.1	4.2
STCC	35.3	319.2	28.8	11.1	9.6
NTNO	12.7	205.3	15.6	13.3	4.9
NTCC	68.1	356.4	28.3	16.3	13.2
ANOVA			*P*-values		
Tillage	0.1155	0.0901	0.4927	0.9886	0.5077
Cover	<0.0001	<0.0001	<0.0001	0.1741	<0.0001
Tillage x cover	0.0875	0.9261	0.1284	0.0294	0.2894
Soil depth (5 – 15 cm)	9.1	154.2	13.9	12.2	3.8
Tillage					
ST	10.1	170.4 a	14.6	13.6	4.2 a
NT	8.2	138.0 b	13.2	10.8	3.5 b
Cover crop					
CC	11.9 a	181.9 a	17.7 a	10.4 b	4.8
NO	6.4 b	126.5 b	10.2 b	14.0 a	2.9
STNO	7.3	136.3	10.4	16.0	3.1
STCC	13.0	204.5	18.9	11.2	5.2
NTNO	5.5	116.7	10.0	12.0	2.7
NTCC	10.8	159.3	16.5	9.6	4.3

ANOVA			*P*-values		
Tillage	0.0995	<0.0001	0.4121	0.0503	0.0051
Cover	0.0002	<0.0001	<0.0001	0.0102	<0.0001
Tillage x cover	0.8308	0.2019	0.4120	0.5572	0.2984
Soil depth (15 – 30 cm)	9.7	140.1	11.3	13.4	3.5
Tillage					
ST	11.5	154.3 a	11.9	14.9	3.9
NT	7.8	125.8 b	10.7	12.0	3.1
Cover crop					
CC	51..7 a	337.8 a	28.5 a	13.7 b	11.4 a
NO	12.2 b	196.5 b	13.8 b	15.7 a	4.6 b
STNO	6.0	131.0	8.6	17.9	2.8
STCC	17.1	177.6	15.3	11.8	5.0
NTNO	6.6	113.3	8.8	12.9	2.7
NTCC	9.0	138.3	12.6	11.1	3.5
ANOVA			*P*-values		
Tillage	0.2872	0.0033	0.3291	0.0914	0.1356
Cover	0.0165	0.0004	<0.0001	0.0118	<0.0001
Tillage x cover	0.2009	0.4490	0.1136	0.2498	0.3284

†Means within a column for tillage treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher's LSD test at 0.05.

‡ Means within a column for cover crop treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher's LSD test at 0.05.

The interactions indicated in Tables 5a and b, required that WEON data be sorted and analyzed by depth. Cover crop resulted in higher WEON at all three depths for both samplings and there was no impact of tillage system at any depth. The ratio of WEOC: WEON was lower in the CC systems at 5 – 15 cm and 15 – 30 cm layer in the spring reflecting lower C levels in the CC systems. The ratio was also lower in the ST than NT systems in fall 2014, in the 0 – 5 cm depth, but there were no other differences observed in any other depths.

Several interactions among factors were observed for the SHI, thus, data were sorted and analyzed by depth for both the spring and fall datasets. Overall, SHI values were higher in fall 2014 than spring again due to higher temperatures from spring to fall as opposed to fall to spring. Cover crop systems had higher SHI values than NO treatments at all depths for both sampling times with the greatest differences in the shallowest (0 – 5 cm) depth which is not surprising since the SHI is calculated from respiration, WEOC and WEON. The spring and fall samplings differed, however, with respect to the impact of tillage. In the spring, the NT systems had higher values in the shallow than in the 15 – 30 depth, whereas in the fall, NT had higher

SHI values in both the shallow and 15 – 30 cm depths, however, the difference between treatments was less evident in the deeper than shallower depth.

There was no significant relationship between total C and WEOC or total N and WEON at either depth (0 – 15 cm of 15 – 30 cm) for the spring 2014 sampling. However, the factors were correlated in the fall sampling (p=0.04), although the r^2 values were relatively low (0.54 and 0.32 for the 0 – 15 cm and 15 – 30 cm C data, and 0.44 and 0.45 for the N data at 0 – 15 cm and 15 – 30 cm).

Table 5b. Soil Health Tool determinations of 1-day respiration, water extractable organic carbon, water extractable organic nitrogen, the ratio of water extractable carbon to nitrogen, and the soil health calculation for standard tillage (ST), no-tillage (NT), with (CC) and without (NO) cover crops at 0-5 cm, 5-15 cm, and 15-30 cm soil depths in Five Points, CA in the fall of 2014.

Source of variation	1-day CO_2-C	Organic C	Organic N	Organic C:N	Soil Health Calculation
	ppm	ppm	ppm		
Soil depth (0 – 5 cm)	110.4	344.3	36.5	9.4	18.1
Tillage					
ST	45.6 b†	256.1 b	29.0 b	8.8 b	10.0 b
NT	175.2 a	432.5 a	44.0 a	10.1 a	26.2 a
Cover crop					
CC	182.7 a‡	430.7 a	45.2 a	9.4	27.1 a
NO	38.2 b	257.9 b	27.8 b	9.4	9.2 b
STNO	25.0	209.7	24.7	8.5	7.1
STCC	66.2	302.5	33.4	9.0	13.0
NTNO	51.4	306.2	31.0	10.3	11.3
NTCC	299.1	558.8	57.1	9.8	41.2
ANOVA			*P*-values		
Tillage	<0.0001	<0.0001	<0.0001	0.0035	<0.0001
Cover	<0.0001	<0.0001	<0.0001	0.9904	<0.0001
Tillage x cover	<0.0001	0.0002	0.0004	0.1870	<0.0001
Soil depth (5 – 15 cm)	36.3	273.6	31.4	8.8	9.5
Tillage					
ST	34.8	254.5 b	29.8	8.5	9.0
NT	37.8	292.7 a	32.9	9.0	10.0
Cover crop					
CC	52.6 a	325.0 a	36.5 a	9.0	12.2 a
NO	20.0 b	222.2 b	26.2 b	8.5	6.8 b

STNO	19.8	209.2	26.2	7.9	6.7
STCC	49.7	299.7	33.3	9.0	11.3
NTNO	20.2	235.2	26.2	9.1	7.0
NTCC	55.4	350.3	39.7	8.9	13.0
ANOVA			*P*-values		
Tillage	0.5526	0.0337	0.1745	0.1084	0.2080
Cover	<0.0001	<0.0001	0.0002	0.2044	<0.0001
Tillage x cover	0.6046	0.4737	0.1668	0.0763	0.3687
Soil depth (15 – 30 cm)	16.4	191.9	24.0	8.1	5.9
Tillage					
ST	16.0	182.2	22.6	8.2	5.5 b
NT	16.8	201.5	25.4	7.9	6.2 a
Cover crop					
CC	18.7 a	217.6 a	26.4 a	8.3	6.7 a
NO	14.1 b	166.1 b	21.6 b	7.8	5.1 b
STNO	14.0	154.6	20.1	8.0	4.6
STCC	18.1	209.8	25.0	8.4	6.4
NTNO	14.2	177.6	23.0	7.7	5.5
NTCC	19.3	225.5	27.8	8.1	7.0
ANOVA			*P*-values		
Tillage	0.4191	0.0800	0.0517	0.4898	0.0176
Cover	<0.0001	<0.0001	0.0020	0.2157	<0.0001
Tillage x cover	0.5553	0.7322	0.9986	0.9506	0.6097

†Means within a column for tillage treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher's LSD test at 0.05.

‡ Means within a column for cover crop treatments at each soil depth followed by the same uppercase letters are not significantly different according to Fisher's LSD test at 0.05.

Our data from the SHI reveal that sustained cover cropping may have pronounced effects on soil health and also on the generally more surface-related improvements that were seen in the NT systems. Our dataset thus serves as a test or application of the SHI and other determinations of soil physical functions provided by the NRCS Soil Quality Test Kit in conjunction with standard laboratory determinations of soil total C and N as a potential battery of soil health diagnostic indicators that may be useful in monitoring efforts aimed at determining time-course changes in soil function.

Yield data for the systems that were evaluated in this long-term study have been reported previously for 2000 to 2009 (Mitchell et al., 2015), and for 2010 to 2014 (Mitchell et al., 2016;

Mitchell et al., In press). For the 2000 – 2009 period, tomato yields were 9.5% higher in the NT vs. ST systems and 5.7% higher in NO vs. CC systems. The ST cotton yields were 10.0% greater than NT yields and 4.8% greater in NO systems overall from 2000 to 2009, but yield patterns were not consistent from 2005 to 2009, and there were no yield differences between systems for cotton from 2010 to 2013. The specific differences in yields among the tillage and CC systems resulted, we believe, from various 'learning curve" challenges that the alternative management approaches posed including stand establishment difficulties of the transplanted tomatoes into CC surface residue and also for cotton plant establishment into residues during the early years. Yield data for sorghum in 2014 and 2015 were combined as there were no interactions between the years and treatments. Tillage or CC had no effect on grain yield indicating that similar yields can be achieved with NT as with ST (Mitchell et al., 2016). The lack of a yield reduction with CC was an important finding because soil moisture depletion by cover crops in semi-arid and arid areas is a concern for subsequent crops (Mitchell et al., 2015). These results indicate that attention to maintaining yield stability as a part of the transition to improved soil health is a critical aspect (Lundy et al., 2015; Pittelkow et al., 2015). They also suggest that the several presumed indicators of improved soil function, or health, (infiltration, aggregation, resistance to slaking, respiration, and both total and WEOC and WEON) that were found in this study with NT and CC, did not necessarily result in increased crop yields. There may, however, be other important metrics for gauging the overall value of these practices in this region including lower production costs, reduced inputs, water conservation, higher C and N storage in the crop/soil system, as well as the ability to lower dust or particulate matter emissions (Baker et al., 2005; Madden et al., 2008).

After 14 years of the tillage and CC treatments, soil C content in the 0 – 30 cm depth increased relative to the initial condition in 1999 for all treatments (Mitchell et al., 2015). Initial soil C averaged 19.72 t ha^{-1} in 1999 for all treatments. The NTCC treatment had the greatest net increase in soil C with 29.1 t ha^{-1} more in 2014 than in 1999, followed by the NTNO with 21.6 t ha^{-1}, the STCC with 16.8 t ha^{-1},and the STNO system with 11.5 t ha^{-1} additional C.

4. Conclusions

Cover cropping and NT practices positively affect soil health in California's SJV. Though this response is expected in rainfed and humid systems, the magnitude of the response is not well established for arid irrigated agricultural systems. Our results showed that CC and NT practices can have a large impact on soil health in arid, irrigated agricultural systems without directly influencing immediate crop yields. This may be a positive attribute as popular belief in the SJV is that NT and CC systems are detrimental to crop yields. When considered in the aggregate, our data point to significant functional benefits being derived from the overall improvements in soil chemical, physical and biological properties and reinforce the value of future efforts to expand the adoption of conservation agriculture systems in the region to improve soil health. Information developed by this study may be useful to farmers in California's SJV who have lacked data on cost-benefit tradeoffs associated with CC and NT practices. Our findings may also be relevant for other similar regions in which there is interest in adopting these practices to achieve food security and sustainability goals.

Figures

Figure 1. Map of California' San Joaquin Valley in western United States. ■ indicates approximate location of Five Points, CA

Figure 2. Total annual precipitation (1999 to 2014) and the 30-year average (represented by the dotted line) at the University of California, West Side Research and Extension Center, Five Points, CA.

Figure 3. Percent surface residue in August 2014 for tillage and cover crop treatments in Five Points, CA. Bars with the same letter within each tillage system are not significantly different according to Fisher's LSD test at 0.05 level. Analysis was conducted on arcsine square root transformed data.

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Trade-offs between winter cover crop production and soil water depletion in the San Joaquin Valley, California

Journal of Soil and Water Conservation 70(6):430-440, 2015

Abstract:

Cover crops are currently not widely used in annual crop production systems in California's semi-arid Central Valley due to concerns about lost opportunity costs and uncertainties about water use. From 1999 through 2014, we quantified cover crop biomass production for a variety of mixtures under winter precipitation and limited supplemental irrigation. In a separate study, we also determined changes in soil water storage under three cover crop mixtures compared to fallowed plots during two (2013 and 2014) winter periods to investigate tradeoffs associated with water use by cover crops in this region. Over the 15 years of the project that were characterized by recurring drought, a total of 22.8 Mg ha^{-1} of aboveground cover crop biomass was produced with a total precipitation of 209 cm and 20 cm of supplemental irrigation applied in 1999, 2012, and 2014. Cover crop biomass varied from 0.39 Mg ha^{-1} in the low precipitation period (winter 2006 – 2007) to 9.34 Mg ha^{-1} (winter 2000 – 2001). Soil water storage in the sampled depth (0 – 90 cm) for the fallow and each of the cover crop mixtures was compared each year from January to March, the primary growing period for cover crops in this region. Net soil water storage increased during this period by 4.8 and 4.3 cm in 2013 and 2014, respectively for the fallow system but in the cover crop mixture plots, there was no additional water storage. Instead, water use by the cover crop mixes resulted in a negative water balance over the cover crop growth period on an average of 0.47 cm and 0.26 cm in 2013 and 2014, respectively. Thus, compared to the fallow system, cover crops depleted 5.3 cm and 0.67 cm more water from the 0 – 90 cm profile in 2013 and 2014, respectively. From this long-term systems research, we conclude that while vigorous growth of winter cover crops in the Central Valley of California may not be possible in all years due to low and erratic precipitation patterns. There may be benefits in terms of providing ground cover residue, and photosynthetic energy capture in many years. However, cover crop biomass production may come at a cost of soil water depletion in this semi-arid, drought-prone region.

Key words: residue-ecosystem services-conservation agriculture-soil water evaporation-conservation tillage

The value of using cover crops to improve the efficiency and productivity of cropping systems while also minimizing adverse environmental impacts has been documented (Creamer and Baldwin 2000; Sainju et al. 2001, Harrison et al. 2004; Snapp et al. 2005; Wang et al. 2006; Schipanski et al. 2014). A growing body of research has been developed, for instance, on cover crop adaptability and management for such production system goals as non-chemical weed suppression (Norsworthy et al. 2005; Isik et al. 2009, Kumar et al. 2009), nitrogen (N) provision (Creamer and Baldwin 2000; Schomberg et al. 2006, Schomberg et al. 2007, and Lenzi et al. 2009), and a variety of soil function improvements including increased carbon (C) storage, fixation of N by legumes, N mineralization from cover crop residues and the ability to support crop production through internal nutrient cycling thereby reducing use of synthetic fertilizers and associated fossil fuel emissions (Schipanski et al. 2014) and ecosystem services (Follett 2001; Alcantura et al. 2011; Ruiz-Colmenero et al. 2011; Schipanski et al. 2014).

Although the USDA National Agricultural Statistics Service has begun to include questions on cover crop use in upcoming Agriculture Census Surveys, there is currently no consistent survey tool available and thus, data on the extent of cover crop use in the US have been difficult to acquire. A recent survey of the 18-state Mississippi River Basin in 2011 found over 0.7 M ha or about 2 percent of the region's cropland planted to cover crops (Bryant et al. 2013). Such surveys have not been conducted in California's semi-arid, highly productive Central Valley (CV), but estimates of current cover crop use in the state's annual cropping systems are also quite low due to farmer concerns about opportunity costs involved in forgoing cash crop income (Brennan and Boyd 2012), the cost and availability of additional water needed to grow a cover crop particularly during periods of drought, and depletion of the winter soil water reserve for spring-seeded annual crops by the cover crop. While Brennan and Boyd (2012) recently anticipated an increase in cover cropping on irrigated cropland in California's Salinas Valley as a management tool to reduce runoff and nitrate losses from fields, decisions to include cover crops into CV cropping rotations are more difficult to justify. This difficulty may remain until accurate water use requirements of the crops are properly documented and tradeoffs between the costs and benefits associated with cover crops are well characterized. Cover crop trait selection options for something as important as low soil water depletion have also not been well addressed (Snapp et al., 2005; Wilke and Snapp, 2008). Snapp et al. (2005) provided a thorough review of the general literature on cover crop adoption and the more localized farmer experience base with cover crops in Michigan and concluded that significant benefit can accrue from cover cropping from environmental enhancement to improved cropping system health. The authors further suggested that improved knowledge concerning management practices is important in tipping the balance toward greater adoption.

An additional, yet currently under appreciated, positive attribute of cover crops is their potential role to provide surface residues to CV cropping systems. In regions of the world where no-tillage or reduced tillage systems are common – such as Brazil, Argentina, Paraguay, Canada, Western Australia, the Dakotas and Nebraska – generating and preserving residues are important parts of management and are major, even primary, goals of sustainable production (Crovetto 1996, 2006). Value is derived from residues in several ways: reduced erosion (Shelton et al. 2000; Skidmore 1986), provision of C and N to soil organisms (Crovetto 2006), reduced soil water evaporation (Klocke et al. 2009; van Donk et al. 2010). Early work by Unger and Vigil (1998) suggested that the inevitable soil water loss associated with cover crops in semi-arid regions such as the CV may be offset or recovered through the use of residue-preserving and reduced soil disturbance practices such as conservation tillage (CT).

Because many of the reported benefits that may be provided by cover crops have relevance to the goals of farmers in the CV to improve soil tilth, add organic matter to the soil, and improve agroecosystem productivity and sustainability, we took advantage of a unique, long-running cropping systems study that has been underway in the CV since 1999. Our major goal was to quantify cover crop biomass production in the CV under winter precipitation and limited supplemental irrigation and to determine the effects of prior crops and tillage management on cover crop dry matter accumulation. Specific questions of interest to the CV were: (i) to what extent is largely rainfed cover crop biomass production feasible? (ii) what levels of C and N may be provided by common cover crop mixtures during the November – March window? (iii) what levels of residue cover are attained by the sustained use of cover crops when incorporated either as 'green manures' or left as surface mulches? and (iv) what do cover crops do to winter soil water storage patterns compared to fallowed soils? Answers to each of these questions are important in helping farmers in the CV rationalize the addition of cover crops to their current cash crop rotations.

Materials and Methods

History of the long-term National Research Initiative (NRI) Conservation Agriculture Systems Project. In the fall of 1999, a group of CV farmers, USDA Natural Resources Conservation Service (NRCS), private sector and university partners initiated the NRI Conservation Agriculture Systems Project. The objective of the project was to develop information on CT production systems and their ability to reduce particulate matter emissions related to the historically high soil disturbance practices that had been used in the region for over 80 years since the advent of irrigation wells in the 1930's. At the time the NRI Project was started, CT practices were used on less than 2% of annual crop acreage in the CV (Mitchell et al. 2007) and informal estimates of the extent of cover cropping were on a similar level. Since 1999, the project has consistently implemented cover crop and tillage system comparisons that differ in terms of soil disturbance intensity and organic matter inputs (Mitchell et al. 2006, 2008, 2009; Veenstra et al. 2007). Various aspects and findings of the early stages of this long-term study have been previously reported including impacts of CT on soil C and N (Veenstra et al. 2006, 2007; Mitchell et al. 2009), dust emissions (Baker et al. 2005), and economics (Mitchell et al. 2009). In this paper we add information on the biomass production of the cover crop systems and soil water balance from 1999 through 2014.

Cropping systems descriptions and 15-year cover crop biomass production study. The study site is located at the University of California's West Side Research and Extension Center (WSREC) in Five Points, CA (36°20′29″N, 120°7′14″W). The field size was 427 m by 100 m and the soil type was Panoche clay loam (fine-loamy, mixed superlative, thermic Typic Haplocambids) (Arroues 2006) with a particle size distribution of 25% sand, 37% silt, and 39% clay. During the year before the onset of the study, a uniform barley (*Hordeum vulgare*) crop was grown and removed as green chop silage to even out differences in soil water and fertility that may have existed due to previous research.

The 3.56 ha field consisted of 32 plots each 10-m wide by 100 m long with 10-m buffer or border plots between treatment plots (Baker et al. 2005). The field was divided into two halves; a tomato (*Solanum lycopersicum)*-cotton *(Gossypium hirsutum L.)* rotation was used in one half, and a cotton-tomato rotation was pursued in the other half to allow tomato and cotton plantings to occur within each year. Management treatments included a factorial arrangement of tillage and cover crop which included standard tillage without cover crop

(STNO), standard tillage with cover crop (STCC), conservation tillage without cover crop (CTNO), and conservation tillage with cover crop (CTCC). Each treatment was replicated four times in a randomized complete block design on each half of the field. Treatment plots consisted of six beds, each measuring 9.1 x 82.3 m. Six-bed buffer areas separated tillage treatments to enable the different tractor operations that were used in each system. A cover crop mix of Juan triticale (*Triticosecale* Wittm.), Merced ryegrain (*Secale cereale* L.) and common vetch (*Vicia sativa*) was seeded using either a 5-m John Deere 1530 no-tillage seeder (Moline, IL) or a 5-m Sunflower 1510 no-till drill (Beloit, KS) at 19 cm row spacing and at a rate of 89.2 kg ha^{-1} (30% triticale, 30% ryegrain and 40% vetch by weight) in late October in the STCC and CTCC plots and irrigated once with 10 cm of water in 1999 (Table 1). The legume species was inoculated with its particular rhizobium before seeding. In each of the subsequent years through 2012, no irrigation was applied to the cover crops, which were planted in advance of winter rains. In 2012 and 2014, 5 cm of irrigation water were also applied to establish the cover crops for a total of 20 cm of supplemental irrigation over the 15-year period. Beginning in 2010 and then persisting through 2014, the basic cover crop mixture was changed in an attempt to diversity it as indicated in Table 1.

Grass-reference evapotranspiration (ETo), total precipitation, soil temperature, and other climatic data from November through March of each year were acquired from a California Irrigation Management Information System (CIMIS) weather station located about 200 m from the study site. Percent residue cover was determined on four occasions during the 15 year study using the line transect method (Bailey, 1983) by taking two random 30-m transects in each tillage system plot. Cover crop biomass was determined usually in mid-March by harvesting all aboveground plant material in a 1 m^2 random area in each plot, drying the material to constant weight, and weighing. The N and C content of the cover crop was determined using a Carlo Erba analyzer (Veenstra et al. 2006).

Cover crop water depletion study. In a nearby field with a nine-year history of no-tillage at the University of California WSREC, comparisons of changes in soil water storage under three cover crop mixes and winter-fallowed bare soil were conducted between November and April in 2012-13 and 2013-14. Cover crop seeding and termination information for these studies is provided in Table 2. These cover crop mixtures represented a variety of common, commercially-available materials that are known to be adapted to the CV (Mitchell et al. 1999). Following a pre-seeding application of 112 kg ha^{-1} of 11-52-0 fertilizer by a 5 m-wide John Deere 1560 no-till grain drill, the cover crop mixtures were seeded as indicated in Table 2 using the same drill because the study field had not been fertilized for a number of years prior to the start of this work, but perpendicular to the direction of preplant fertilizer application. Bare untilled plots that represented conventional winter fallow conditions were maintained weed free by application of a 2% solution of glyphosate [N -(phosphonomethyl glycine)] as needed. Each cover crop and fallow plot was 10 m wide and 30 m long and was replicated three times in a randomized complete block experimental design in each year. Ten centimeters of water were applied by sprinkler in each year to establish the cover crops. These irrigations were also applied to the fallow plots.

Aboveground cover crop biomass fresh weights were determined ten times each year by harvesting and weighing all plant materials within a random 1 m^2 area in each plot. The biomass was then dried to constant weight for dry weight and N content determinations. Volumetric soil water content was monitored twice weekly in all plots using a neutron hydroprobe (Campbell Pacific Nuclear, Martinez, CA) at depths of 15, 30, 60, 90, 120, 150, and 180 cm using a calibration equation that computed volumetric soil water content using raw counts from the probe detector that was developed for the site (R^2 = 0.93). Soil water content for each measurement depth in the 0 – 90 cm depth were then added and the total amount of water for the cover crop treatments was compared during the January through March 27 period with the amount of water in the fallow treatment for each year.
Data for cover crop biomass, surface residue cover, cover crop N content, and soil water content in the 0 – 90 cm depth were analyzed separately for each year. Assumptions of ANOVA were tested prior to running the general linear model (GLM) procedures in SAS and data were log transformed when they failed to meet the assumptions. Mean separation tests were conducted on transformed data but non-transformed means were presented. All data were analyzed using GLM procedures of SAS using an alpha level of 0.05 for significance. Tillage and cover crop were considered as fixed effects, and year and replication were considered as random effects. Interactions between tillage and cover crop were also tested as appropriate.

Results and Discussion

Weather conditions

Despite the CV's Mediterranean-type climate with most precipitation occurring during the cooler winter months, there was a long-term average water deficit of about 12.5 cm between ETo and precipitation during the 5-month November through March period in Five Points, CA based on both 30-year averaged data (Table 3) and the actual data during the 15 years of this investigation (Table 4). These data, however, underscore the theoretical basis for identifying this winter growing 'window' as being perhaps the most reasonable period for attempting to insert cover crops into the region's cropping systems during a time when daily temperatures and thus ETo are relatively lower in comparison to summer trends.

Winter precipitation from November through March for the 2000 to 2014 period was about 2.2 cm lower than the long-term average which ranged from a high in 2011 of 31 cm to a low of 6.5 cm in 2014, this marked one of the driest winters in history (Howitt et al. 2014). It is not only the winter seasonal total precipitation, but also the timing of precipitation that is important to sustain largely rainfed productive cover crop biomass accumulation. Ideally, for the November to March window, an early November onset of precipitation with the bulk of remaining typically-available winter rain coming soon thereafter in December and early January might be the best overall precipitation timing pattern for optimal cover crop biomass production. Long-term average data, however, indicate that December and January actually tend to have the lowest monthly average precipitation of the five winter months and the unpredictability of precipitation during this critical period is very important for eventual precipitation -limited growth as seen in Table 4. Thus, if small supplemental amount of irrigation is applied during this winter cover crop season, they might best be scheduled during the December – January early period to gain maximum value.

Over the 15 years of the study, the average planting date was November 8 and the average termination date was March 22 for a total number of growing season of 135 days. This growing window mirrors quite closely the typical intercrop period following the harvest of most summer and fall crops and the establishment of many spring and summer crops that are customarily produced in the CV. Thus, it provides a reasonable time frame when off-season cover crops might be integrated into a common production schedule and is in line with schedules used by the few CV row crop farmers who currently use cover crops.

Comparing historically-averaged ETo for July and August, which totals 43.5 cm, to ETo for December and January, which is 6.8 cm, the potential atmospheric demand for water loss via evapotranspiration is only about 15% during the winter than it is in the summer in the Five Points, CA area. Thus, if suitable cover crop selections that grow well during this winter window are identified, their potential water use via transpiration would be lower and their water use efficiency (WUE) would be higher relative to summer cover crops.

Aboveground biomass and N content

The aboveground cover crop biomass was affected by the year and the previous crop in the rotation and there was an interaction between these two factors. Therefore, data were analyzed separately for each year. The interaction was primarily caused by the lack of significant difference in cover crop biomass as an effect of the previous crop in five out of the 15 years; otherwise, in the other years, the cover crop biomass was always greater in the plots following tomato than the plots following cotton (figure 1). Cover crop aboveground biomass production averaged 3.42 Mg ha^{-1} over the 15 years of the study (figure 1). There was, however, large variability in the amounts of biomass that was produced in a given year due to differences in climatic conditions ranging from 0.039 Mg ha^{-1} in the 2006 – 2007 winter, to 9.34 Mg ha^{-1} in the first winter. This finding is consistent with the observation of Brennan and Boyd (2012) that cover crop performance varies considerably among years. In years when small supplemental sprinkler irrigations were applied (2000, 2013, and 2014), cover crop growth was higher than the 15-yr average by 2.75, 1.22, and 1.14 times in 2000, 2013, and 2014, respectively. Productivity in 2013 and 2014, which were years with relatively low precipitation, were only modestly higher than the long-term average.

Over the 15 years, the average total of 3.42 Mg ha^{-1} of aboveground cover crop dry biomass that were produced, represented inputs of 1.20 Mg ha^{-1} of N and 21.7 Mg ha^{-1} of C based on cover crop tissue N and C determinations made periodically during the course of the study (data not shown). The cover crop biomass production observed in this study under largely rainfed winter conditions with only small amounts of supplemental irrigation in three of the 15 years is generally in the intermediate range of reported cover crop biomass production in the region (Mitchell et al. 1999). With 8 cm of irrigation water, biomass of single-species cover crops such as triticale (*Triticosecale*) or wheat (*Triticum aestivum*) during the same November to mid-March window of 1.12 to 12.23 Mg ha^{-1} of dry matter was achieved (Mitchell et al., 1999). Percent surface residue cover was affected by both cover crop and the type of tillage that was used in this study, whether CT in which cover crops were left as mulches, or standard tillage in which they were incorporated into the soil as green manures for each of the three measurement dates (Table 5). However, there was no interaction ($P = 0.84$) between tillage type and cover crop for percent residue cover. The combination of cover crops with CT consistently had higher percentage of residue cover than with ST.

The determination of the impacts of these cover crops on subsequent crops was beyond the scope of this paper. Those relationships have been reported in earlier studies. Mitchell et al. (2015) observed that yield differences in both cotton and tomato in treatments with and without cover crops were not consistent between years. Further, presence of a cover crop prior to tomato, generally resulted in lower or similar yields between CT and ST in most years of the study due to difficulties establishing transplants as well as slower seedling early-season growth rates in cover crop plots (Mitchell et al., 2009). Presence of a cover crop for cotton, while not necessarily resulting in lower yields (Mitchell et al., 2015), presented additional crop establishment challenges that need management attention and successful implementation to avoid yield loss (Mitchell et al., 2008).

There are examples of successful crop production in semi-arid regions, other than the CV, that may be instructive for increasing winter cover crop productivity. Farmers in Western Australia, for instance, have been coupling no-tillage, high residue production techniques under similar rainfed regimes for a number of years and achieving economically viable wheat grain yields with an average of 30.5 cm of precipitation (Crabtree 2010). Other work with conservation agriculture practices that reduce soil disturbance and preserve residue, so as to increase precipitation capture and storage and reduce soil water evaporation losses (Klocke et al. 2009; von Donk et al. 2010; Mitchell et al. 2012), may thus have increased relevance and potential for adoption in future CV cropping than they have now. Merging of these practices along with cover cropping may increase the overall water use efficiency of CV production systems in the future (Mitchell et al. 2012) and improve the economic tradeoffs or reduce risks associated with cover cropping in this region.

The effect of the legume/triticale cover crop on soil temperature is seen in figures 2a and b for 2013 and 2014, respectively. In general, the combination of the cover crop canopy as well as surface residues from prior no-tillage management in each cover crop plot resulted in soil temperatures at the 10 cm depth being an average of 5 to 8°C lower under the cover crop relative to bare soil which may contribute to decreased soil water evaporation. Lower soil temperatures under surface mulches, however, may also result in slower early-season growth of crops such as tomato that follow the cover crop (Mitchell et al., 2009).

Biomass accumulation for the cover crop mixtures used in the soil water study for 2013 and 2014 is shown in figures 3a and b. There was a difference between the years in cover crop biomass and an interaction between year and cover crop type. Therefore, data were analyzed separately for each year. More biomass was produced in 2013 than in 2014 by each mixture with the legume/triticale mix having the highest production with 5Mg ha^{-1} and 4.7Mg ha^{-1} in 2013 and 2014 (figure 3a and b). Although, initially, more biomass was produced by the Brassica treatment in 2013 the total biomass at termination of the cover crop was greatest in the legume/triticale mixture while there was no difference in total biomass between the Brassica and legume-only plots (fig 3a). However, such differences in the initial growth period was not observed in 2014 (figure 3b). In 2014, the total biomass was greatest in the legume/triticale mixture and least in the legume-only plots whereas the biomass in the Brassica plot was intermediate (figure 3b). Accumulation was more gradual in all mixtures and typified routine cover crop growth dynamics in 2013, whereas the pattern of growth in 2014 indicated a longer lag in vegetative biomass increase perhaps due to low and late precipitation of this year. Biomass accumulation in both 2013 and 2014 was about one-third of what might be expected for similar species mixes in this region with supplemental irrigation (Mitchell et al. 1999). There was more consistent and evenly distributed and higher amounts of precipitation during the 2012 – 2013 five-month winter period from November through March than in 2013 – 2014 (figure 4) and this may have accounted for the higher cover crop growth that was measured during the first year.

Data for N content of the three cover crop mixtures was analyzed separately for each year as the samples were taken at different times during the two years (figures 5a and b). Significant differences between the cover crop mixtures in N content during different sampling dates in each year of the study. In 2013, at the initial sampling date, the N content in the biomass of the Brassica plots was the greatest followed by the legume plots. The least amount of N content was in the legume/triticale mixture plot (figure 5a). Although this difference did not hold true at each sampling date, in general, the N content in the biomass of the Brassica plots was generally greater than the other cover crop mixtures. Similarly, for most part of the season including at termination, the N content of the legume/triticale cover crop plots was greater than that of the legume-only plots (figure 5a). In 2014, the trends were different. For example, the N content in the legume-only plots was greatest at the first and last sampling dates (figure 5b). Contrary to 2013, the least N content was in the legume/triticale plots. Nitrogen content tended to decrease during each winter growing season from about 4% to 2 – 3% at the time of termination in late March. Because all aboveground biomass within a sampling area was harvested, including weeds, expected higher N content for the legume mix might have been diluted particularly in 2013 (Mitchell et al. 1999). Using biomass and N-content data for each mixture for the final sampling dates in each year, 127, 52, and 136 kg of N ha^{-1} were accumulated in the brassica, legume and legume/triticale mixes in 2013, and 46, 68, and 85 kg ha^{-1} N for the same species, respectively, in 2014. The risk of N loss by leaching in this region during the winter growing period would be relatively low due to low precipitation rates. Therefore, a proportion of these measured cover crop tissue N levels is assumed to have derived from soil pools that might otherwise have provided N to subsequent cash crops in the following spring.

Soil water content

Volumetric soil water content data for the 0 – 90 cm depth from the fall of 2012 through the summer of 2014 for the cover crop soil water depletion study are shown in figure 6 for the three cover crop mixtures and the fallow systems. For the purposes of this analysis, we compared soil water content as measured by neutron probe from the 0 – 90 cm depth from January 5 in 2013 and January 2 in 2014 through March 27, a reasonably average termination date in each year and determined changes in stored water in each system during this time. In general, soil water content was similar among all treatments at the start of the winter growing season in early January with a 0.22 cm difference between the four treatments in 2013 and a 1.64 cm difference between treatments at the start of 2014 for the 0 – 90 cm depth.

Total soil water storage in the 0 – 90 cm profile for the fallow and each of the cover crop treatments compared across the January to March 27 period differed between years and there was a year by treatment interaction. Therefore, data were analyzed separately for each year. In 2013, fallow system had the most amount (4.8 cm) of total soil water and it was greater than the cover crop treatments (figure 7). There was no difference between the cover crop treatments in total soil water storage and ranged from -0.57 cm to 0.12 cm Similarly, in 2014, the fallow plots had the most amount (0.43 cm) of total soil water (figure 7). However, contrary to 2013, cover crop treatments differed in total soil water. The cover crop mixture and Brassica plots had similar amount of total soil water but the legume plot had less total soil water than the cover crop mixture plots. Compared to the fallow system, cover crops thus depleted 5.3 cm more water from the 0 – 90 cm profile in 2013 and 0.67 cm more water in 2014. Most of the difference in soil water depletion between the fallow and cover crop systems occurred during March of each year.

These findings and the range of difference in soil water storage between the no cover crop, bare soil check, and the three cover crop mixtures are generally similar to the findings of other studies. For example, Stivers and Shennan (1991) reported that water content in the 60 cm (24 in) depth was reduced by 2 cm in oat (*Avena sativa* L.) plots, but only by 1 cm in vetch (*Vicia dasycarpa*) plots relative to that in fallow plots in Davis, CA, another predominantly winter-precipitation semiarid region (Unger and Vigil 1998). In slight contrast, in our earlier work in Five Points, CA, 3-year average water contents were 7.4 cm less in barley (*Hordeum vulgare* L.), 7.9 cm less in barley + vetch, and 6.6 cm less in vetch cover crops than in fallow plots (Mitchell et al. 1999). Soil water content in fallow plots increased by 9.4 cm in the first two years, but only by 4.1 cm in the third year when precipitation was lower, as was the case in 2014 of the present study.

Unger and Vigil (1998) reviewed the effects that cover crops have on soil water relations and concluded that because cover crops use water they may be more suited to humid and subhumid regions than to the hot summer Mediterranean climate of California’s CV (Peel et al. 2007). The overall effect of cover cropping on soil water relations depends on the timing and amount of precipitation during the winter, water infiltration and soil evaporation, as well as transpiration rate by the cover crop. Where precipitation is limited as it is in the CV, there is thus a definite risk that cover crops will deplete soil water to some extent and reduce yields of subsequent cash crops because of reduced soil water storage. Unger and Vigil (1998) point out, however, that these losses in storage may be recovered by CT that involves crop residue maintenance on the soil surface and reduced soil disturbance. Indeed, our own recent work with surface residue mulches and no-tillage in the CV has demonstrated this very important tradeoff (Mitchell et al. 2012). Coupling no-tillage or reduced tillage with practices preserving high residues reduced summer soil evaporation losses by about 10.2 cm which is about 13% of a typical summer crop's evapotranspiration (Mitchell et al. 2012) and roughly equal to the determinations of winter cover crop water use reported here. There are many examples of benefits derived from generating and preserving residues as a means for reducing soil water evaporation (Klocke et al., 2009, van Donk et al., 2010, Crovetto, 1996, 2006), but no work has been done to evaluate potential benefits and tradeoffs associated with high residue-preserving production practices. Therefore, this is an important area for future research.

Summary and Conclusions

This study illustrates the importance of long-term systems research in providing clear, robust implications of crop management options that may not be apparent in shorter duration investigations. Data from this study provide invaluable information in terms of inter-annual variation in cover crop biomass and soil-water depletion in response to variations in climatic conditions. Our data suggest that while vigorous growth of winter cover crops in this area of the CV may not be possible consistently in all years due to the low and erratic precipitation patterns, in most years there may be benefits in terms of providing some amount of crop cover and increasing the efficiency of the cropping system to capture photosynthetic energy throughout a year, the cycling and capturing of both C and N, and of adding biological diversity and activity to the soil during periods that might otherwise be devoid of such soil building life (Ferris et al. 2004; DuPont et al. 2009).

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The potential for conservation tillage adoption in the San Joaquin Valley, California: A Qualitative study of farmer perspectives and opportunities for extension

Also during the course of our conducting this CIG project, we have also prepared a manuscript based on survey and extensive interview information related to conservation tillage adoption in California. This work is now in final revision review in the journal PLOSOne. Upon our receipt of its final resolution by the editors of this journal, we will forward it to NRCS.

Discussion of Quality Assurance

With regard to the quality of our data, each of the above-mentioned pieces of work that have been accomplished under this CIG project, has or is undergoing formal peer-review in terms of scientific rigor, methodology, analysis and interpretation. We believe that these publication outcomes amply speak for themselves in terms of the quality of our procedures and methodologies. We note, as also mentioned above, that we did slightly reorient our core objectives in this work emphasizing more overall soil health than the nitrogen aspects that were more prominent in our original proposal. We believe that this slight redirection of effort has been amply justified in light of the opportunities we had in this project to add to the scant knowledge base on soil health in California by using the unique field resource we had in our Five Points, CA study site.

Findings

Specific findings have been described in the very detailed work above and in our summary.

Conclusions and Recommendations

In sum, this project has not only provided a uniquely ambitious and now growing network of farm demonstrations related to conservation agriculture in California, but it has also generated a solid amount of fundamental information related to soil functional resilience that may be achieved by the combined long-term use of cover crops and no-tillage. This is a basic outcome of our work. This project has shed important light on soil function changes that may result from the sustained use of these conservation agriculture practices and indicates that concrete, significant improvements in overall soil health may be achievable through the use of these management techniques.

This project has generated two types of outcomes. First, we have now demonstrated through our detailed investigations of a range of soil biological, chemical, and physical functions and properties that key soil health indicators change under cover crop and no-till management in California's San Joaquin Valley. This information is new and valuable for this region. Second, we have now created a growing, effective means for further extending this and related information on soil health more broadly in California through our farm demonstration evaluation network that has been created during the course of this CIG project.

For Technology Review Criteria

Neither of the core conservation practices, cover cropping or no-tillage, is at all new within the national practice standards framework of NRCS and therefore we are not necessarily recommending anything novel or unprecedented. However, because these practices are quite new here in California, we believe that we ought to engage in planning discussions with California NRCS leaders and share with them more specifically, the findings of this project. It is our intention within the coming year, therefore, to compile a 'lay person's' summary of the entire body of work that has been accomplished by this CIG project and to share this with NRCS and other stakeholders as a compilation of our investigations.