Arnold Schwarzenegger
Governor

ASSESSMENT OF GREENHOUSE GAS MITIGATION IN CALIFORNIA AGRICULTURAL SOILS

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Prepared By:
Steven De Gryze, Rosa Catala, Richard E. Howitt, and Johan Six
University of California, Davis
Davis, California 95616

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Prepared For:
Public Interest Energy Research (PIER) Program
California Energy Commission

Guido Franco
Project Manager

Linda Spiegel
Program Area Lead
Energy-Related Environmental Research

Ken Koyama
Office Manager
Energy Systems Research

Martha Krebs Ph.D.
PIER Director

Thom Kelly Ph.D.
Deputy Director
ENERGY RESEARCH & DEVELOPMENT DIVISION

Melissa Jones
Executive Director

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Preface

The California Energy Commission's Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

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Assessment of Greenhouse Gas Mitigation in California Agricultural Soils is the final report for the Integrated Assessment of the Biophysical and Economic Potential for Greenhouse Gas Mitigation in California Agricultural Soils project (Contract Number 500-02-004) conducted by the University of California, Davis.

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Abstract

Research has suggested that carbon can be captured through changes in farming practices, thereby helping California reach its greenhouse gas emission reduction goals as put forward under the California Global Warming Solutions Act of 2006, Assembly Bill 32, (Núñez, Chapter 488, Statutes of 2006). This study assessed the potential and economic feasibility of soil carbon sequestration and reduction of trace gas emissions in California agricultural soils. To accomplish this, the researchers integrated databases that include geographic data on environmental factors and land use data with ecosystem simulation models and economic analyses. The resulting assessment tool analyzes land use and management impacts on carbon stocks and associated greenhouse gas fluxes between California agricultural soils and the atmosphere. The study found that adjusting farming practices could reduce greenhouse gas emissions by about 0.5 to 3 megagrams of carbon dioxide equivalent per hectare per year. The variation in this number is mainly on the type of farming practice used. This potential increased in the following order: low nitrogen fertilizer input, reduced tillage, manure application, and winter cover cropping. Even higher potentials could be reached when these single management options are combined. However, the uncertainty around the carbon reduction potentials of a single field remains large. More research is needed to reduce this uncertainty.

Keywords: Agriculture, agricultural management, carbon credits, carbon sequestration, carbon supply curve, greenhouse gases

Executive Summary

Introduction

It has become apparent that California's climate is changing and concerns over greenhouse gas emissions in California have increased. Within the California Global Warming Solutions Act of 2006, Assembly Bill 32, (Núñez, Chapter 488, Statutes of 2006), the possibility exists to offset greenhouse gas emissions through capture and storage of carbon dioxide, or carbon sequestration, as part of a proposed cap-and-trade market system. A recent study concluded that California agriculture has potential for reducing greenhouse gas emissions if certain alternative management practices (such as reduced tillage, cover cropping, and organic farming) are adopted. In the proposed system, farmers who adopt these alternative farming systems leading to greenhouse gas reductions can earn emission credits to be purchased by other parties that exceed their emission cap. This study provides a comprehensive assessment of the biophysical and economic potential for California agricultural greenhouse gas mitigation.

Purpose and Project Objectives

The main objectives of this study were to estimate the biophysical potential of greenhouse gas reduction in California agriculture under different practices (such as cover cropping, conservation tillage, organic fertilization, and low nitrogen fertilizer input systems) at the field, county and regional scale; to perform an uncertainty analysis to evaluate potential risks associated with the adoption of the alternative practices for greenhouse gas reduction; and to construct carbon supply curves that relate the potential amounts of greenhouse gas reduction with the costs for doing so. These three objectives lead to an overall comprehensive objective to evaluate the biophysical and economic implications of providing financial incentives for farmers who adopt alternative cropping practices.

Project Outcomes

A biogeochemical model, which shows the chemical, physical, geological, and biological aspects of the data, was adjusted by standardizing the data by determining the deviation from the mean for certain cropping systems under Californian conditions using data from four long-term experiments. It was concluded that by implementing changes in agricultural management practices, there is a biophysical potential of sequestering approximately 0.5-3.0 megagrams of carbon dioxide equivalent, which is the amount of carbon dioxide in the mixture of greenhouse gases that would have the same global warming effect over a specific amount of time per hectare per year (Mg CO_2-eq ha^{-1} yr^{-1}, with some minor differences between the Sacramento Valley (0.7 to 3.3 Mg CO_2-eq ha^{-1} yr^{-1}) and the San Joaquin Valley (0.5 to 2.5 Mg CO_2-eq ha^{-1} yr^{-1}). The values are net sequestration rates; they are the difference of emissions under alternative and conventional agricultural management. The greatest potentials are achieved by combining alternative framing practices; particularly by combining conservation tillage with manure application, or winter cover cropping with manure application, greenhouse gas emissions were

reduced. Most of this potential is due to increases in soil carbon (that is, 70–90 percent of the mitigation potential is attributable to soil carbon sequestration) which are short-term and temporary. Reducing fertilizer application rates and fuel use (under conservation tillage) provide a more sustainable reduction in emissions, although their capacity is small (on average 0.5 Mg CO_2-eq ha^{-1} yr^{-1}).

Conclusions and Recommendations

Alternative management practices are viable solutions for reducing greenhouse gas emissions when compared to conventional farming, but further research still needs to be conducted to reduce the variability of the estimated emissions from individual fields and groups of fields. This reduction in greenhouse gas will discount the price paid for carbon credits generated by agricultural land management compared to carbon credits from less variable sources. However, this uncertainty is reduced when predictions are made for larger geographical regions and longer durations. Therefore, multi-year and multi-field contracts will be necessary to reduce this possible discount in carbon credit prices for agricultural mitigation and thereby increase the potential of its use to offset emissions.

The uncertainty is most pronounced for nitrous oxide emissions. This is especially problematic because the least amount of data for adjusting and validating the model is available for this greenhouse gas. Therefore, the authors recommend that further research focuses on building a sound and systematic dataset of nitrous oxide fluxes in Californian agroecosystems and the improvement of nitrous oxide emission routines of existing ecosystem models.

Benefits to California

Not only can Californian agriculture play a role in offsetting greenhouse gas emissions, the adoption of the alternative agricultural cropping practices also improves agroecosystem functioning and reduces agriculture's environmental impact. Furthermore, if agriculture can participate in the carbon market, the economical viability of agriculture will increase, resulting in a more sustainable agricultural enterprise in California.

1.0 Introduction

With the recent approval of the California Global Warming Solutions Act of 2006 (AB 32),[1] California committed to a 25% reduction in greenhouse gas (GHG) emissions by 2020. With this commitment, California will play a pioneering role for the United States and potentially for the world. The reduction in GHG emissions will be realized through stringent emission caps and mitigation options. Right now, forestry is the only land use that has existing reporting and certification protocols developed by the California Climate Action Registry (CCAR), a private/public partnership for voluntary GHG reporting. The California Air Resources Board (ARB), which is charged with conducting the rulemaking process for AB 32, is encouraged to incorporate CCAR's standards and protocols. With respect to agriculture, collaborative research on GHG reduction from nitrogen land application is listed as an early action strategy by ARB (early action nr. 31). This strategy involves the identification of methodologies for better characterizing California's nitrogen cycle. With this, ARB recognizes the need to better understand the relationship between nitrogen land application and nitrous oxide formation in California's agriculture.

A number of recent scientific studies and reports have emphasized the potentially significant role for agriculture in carbon sequestration and subsequently in climate change mitigation (Gielen et al. 2002; Pacala and Socolow 2004; Kim and Dale 2005). In 2003, the West Coastal Regional Carbon Sequestration Partnership (WESTCARB) was established by the U.S. Department of Energy (U.S. DOE) to evaluate carbon dioxide (CO_2) capture, transport, and carbon sequestration technologies best suited for the region. According to the WESTCARB project, agricultural land has high potential for increasing its role as a carbon sink through adoption of alternative management practices. These findings were translated into the Conservation Security Act (CSA) in the 2002 U.S. farm bill. Whereas in the past the CSA fostered incentives for the retirement of agricultural land, the CSA now focuses on changing agricultural practices on cultivated lands. Specifically, the act authorized the U.S. Department of Agriculture to make payments to farmers who adopt conservation practices such as conservation tillage.

California, the world's fifth largest supplier of food and other agriculture commodities (CDFA 2006), is characterized by high crop diversity, intensively managed cropping systems, high nutrient input levels, and potentially harmful environmental impacts. California agriculture (and global intensive agriculture more broadly) faces the challenge of reducing these environmental impacts while maintaining agronomic and economic productivity. A carbon credit system presents an opportunity to growers to mitigate GHG emissions by optimizing management practices while providing them with additional gross income to ease the management transition. The additional gross income could be insurance against the increased risk of transition and/or it could be a net income increase. However, whether or not farmers will finally adopt these optimized

[1] Assembly Bill 32 (Núñez), Chapter 488, Statutes of 2006.

practices will depend on their individual expected economic returns and geographically specific agronomic variables under the various alternatives they may face. A carbon sequestration program based on payments to farmers who adopt carbon-sequestering practices affects the profitability of each land use in a specific way, so the analysis of the economic potential of carbon sequestration is a complex exercise that demands a thorough, multidisciplinary approach.

1.1. Background

1.1.1. Biogeochemical Cycling of Carbon and Nitrogen

The terrestrial biosphere exchanges significant amounts of GHGs to and from the atmosphere to an extent that by far outweighs the total human-induced exchanges. Although CO_2 is the best-known biogenic greenhouse gas, two other biogenic GHGs that are also potentially emitted by terrestrial systems are methane (CH_4) and nitrous oxide (N_2O). Under intensive agricultural systems (as those found in California), these trace gases may even dominate GHG emissions. It should be noted here that trace gases differ in their radiative forcing from CO_2. More specifically, one gram of CH_4 has the same radiative forcing as 25 grams of CO_2, and one gram of N_2O has the same impact as 298 grams of CO_2 (Chapter 2 of IPCC 2007a). These values are valid over a time horizon of 100 years. Note that these values are updated from IPCC 2001, in which radiative forcings of 23 for CH_4 and 296 for N_2O were reported. All emission numbers in this document combine the three GHGs and are weighed according to the most recent radiative forcings as reported in IPCC 2007a. They are referred to as the *global warming potential* (GWP) and are expressed in CO_2-equivalents (CO_2-eq). Since total budgets of all three biogenic greenhouse gases (not only of CO_2) are presented in these analyses, the term *GHG mitigation* is preferred over the (albeit more popular) term carbon sequestration.

The main atoms of the three greenhouse gases, carbon (C) and nitrogen (N), are essential elements of all life forms and are abundant in the atmosphere, hydrosphere, and biosphere. The global cycles of these atoms are tightly coupled. Atmospheric CO_2 is taken up by plants and converted into plant tissue through photosynthesis. Once a plant dies, its dead biomass is subject to decomposition by microorganisms, which will convert the plant residues back to CO_2 under aerobic conditions or to CH_4 when not enough oxygen (O_2) is available. The CH_4 produced in the soil can also be oxidized to CO_2 by soil microorganisms in a process called *methane oxidation.* During plant growth, N is taken up by plants through roots mainly in the form of nitrate (NO_3^-) or ammonium (NH_4^+). In addition, microbial communities associated with specific plant species (N_2 fixers) and some free-living microorganisms can assimilate atmospheric N_2 directly. When the plant dies, microorganisms will mineralize the N contained in the dead biomass to ammonium. If the conditions are right (lack of O_2 and ample availability of a C-source), some microorganisms (denitrifiers) reduce nitrate back to atmospheric N_2. This process, called *denitrification,* involves an array of reactions and intermediates. Two of these intermediates—nitric oxide (NO) and N_2O—are gaseous and can escape during

the process. Under different conditions, some organisms (nitrifiers) can convert the ammonium to nitrate, a process referred to as *nitrification.* During this process, N_2O is again an intermediate. If enough mineral N is available in the soil solution and the conditions are right, N_2O production is triggered. In agricultural systems, nitrification and denitrification are prevalent when fertilizer is applied in excess. In conclusion, soils can act both as sources and sinks of each of these three greenhouse gases (see Table 1.1).

Table 1.1. Sinks and sources of the three biogenic greenhouse gases in agriculture

	Sources	Sinks
CO_2	Decomposition of plant biomass	Plant growth through photosynthesis
CH_4	Methanogenesis (rice fields)	Methane oxidation in soils
N_2O	Nitrification and denitrification	

Alternative management practices will only lead to true GHG mitigation if the overall impact of their adoption reduces the net global warming potential determined by fluxes of the three major biogenic GHGs. All three GHGs must be included in an evaluation of management practices. Sometimes practices that sequester C by increasing soil C also increase N_2O emissions. This is because soils with higher C contents often have higher N_2O fluxes, both across a landscape (Robertson and Tiedje 1987; Mosier et al. 1996; Vinther 1992) and within a field (Ambus and Christensen 1994).

1.1.2. Conditions for Greenhouse Gas Mitigation

The emission of GHGs can be mitigated through either (1) an increased conversion of atmospheric C into the terrestrial system, or (2) a decreased emission of the trace gases N_2O and CH_4. First, there are many terrestrial C pools, including aboveground and belowground living biomass, the litter layer, and soil organic carbon (SOC). Only an increase of C in the SOC pool is considered true carbon sequestration. The turnover of C in these other pools (e.g., the litter layer) is very rapid, and increases in these pools are very transient. Therefore, these pools are not taken into account when calculating the amount of C being sequestered.

Increased Conversion of Atmospheric Carbon into the Terrestrial System

Any change in SOC is simply the difference between inputs of C to the soil system and outputs through decomposition. In other words, any agricultural practice that increases the input of C or decreases the decomposition of SOC will lead to an increase in SOC and hence to soil C sequestration (Figure 1.1). Therefore, a first set of management options that lead to C sequestration focuses on increasing the input of C to the soil system. For example, by using manure for fertilizer, a substantial amount of C is added that can be stabilized as SOC. The inclusion of a winter cover crop in cropping systems can also generate a substantial amount of plant biomass carbon. When the winter cover

crop is tilled under in springtime, part of this biomass will be converted into soil organic carbon.

A second set of options that will lead to C sequestration focuses on reducing the decomposition from the SOC pool. An example of this strategy is reducing tillage intensity. Tillage disturbs and homogenizes the soil system and, therefore, increases contact between decomposing organisms and their substrate, SOC. This increased contact will temporarily accelerate decomposition immediately after tillage. In addition, tillage also indirectly affects SOC levels since it disrupts soil aggregates and fungal hyphae, which are known to stabilize soil organic carbon (Six et al. 2004). Therefore, tilled soils have a lower capacity to store carbon compared to undisturbed soils. As a consequence, if the intensity of tillage is reduced, SOC levels can increase during some period of time.

Figure 1.1. Increases in soil organic matter (SOM) input (left side) or reduction in decomposition of SOM (right side) lead to C sequestration

Decreased Emissions of the Trace Gases N_2O and CH_4

Any practice that reduces N_2O or CH_4 emissions is effective in mitigating GHG emissions. It has been observed that N_2O emissions through denitrification are linked to a simultaneous high soil water content, usually quantified as the water filled pore space (WFPS), and to soil nitrate content (Ruser et al. 2001; McSwiney and Robertson 2005). Because of the variable nature of soil water content as influenced by rainfall and evapotranspiration,N_2O fluxes are erratic. When the conditions are right (high soil water, high mineral N content, and available C-substrate), N_2O production starts quickly, even after a few minutes (Davidson 1992). Management practices that avoid these conditions will be effective in reducing N_2O emissions. These practices include:

- **Avoiding over-fertilization shortly before or after rainfall or irrigation events.** Rainfall or irrigation immediately after excess fertilization leads to the ideal conditions for denitrification: great availability of mineral nitrogen, and high soil water contents (Smith et al. 1998; Dobbie et al. 1999). In addition, fertilization generally occurs in the springtime, when temperatures are warm enough for microbial activity, and a significant amount of easily degradable carbon is present in the soil. Sudden increases in water filled pore space stimulate the microbial processes that lead to N_2O emissions, sometimes as soon as 1-2 hours after irrigation. It is to be expected that these peaks slowly attenuate as the

mineral N content decreases upon further development of the crop, toward the end of the growing season.

- **Avoiding the incorporation of crop residues under wet soil conditions.** Crop residues have a great N content. Incorporating these under wet soil conditions will lead to enhanced N_2O losses after incorporation (Kaiser et al. 1998; Baggs et al. 2000). This might be especially important in vegetable production because vegetables are highly fertilized, and the crop residues are high in N (De Neve et al. 2004). Typical C-to-N ratios for vegetable crop residues are between 10 and 15, while they are between 60 and 100 for grain crops (Howard et al. 1962).

1.1.3. Global and Statewide Agricultural GHG Emissions

Land systems have a dominant effect on the global carbon cycle. It is estimated that for the 1990s, about 122.6 gigatonnes of carbon per year (Gt C yr^{-1}) was sequestered globally from the atmosphere through photosynthesis, while about 119.6 Gt C yr^{-1} was emitted through biomass decomposition. Another 1.6 Gt C yr^{-1} was emitted through land-use changes (dominated by tropical deforestation) (IPCC 2007a). In comparison, annual GHG emissions through fossil fuel burning and cement production were estimated at 7.2 ± 0.3 Gt C yr^{-1} between 2000 and 2005 (IPCC 2007a). Agriculture is the largest anthropogenic N_2O source (Bouwman et al. 2002; Smith and Conen 2004; Del Grosso et al. 2005): of the total anthropogenic N_2O emissions of 8.1 teragrams of nitrogen per year (Tg N yr^{-1}), agriculture accounts for 6.3 Tg N yr^{-1} (Bouwman et al. 2002). Note that another 9.6 Tg N yr^{-1} is emitted by natural non-human induced sources. Likewise, agriculture is the largest emissions source for CH_4: of the total anthropogenic source of 428 Tg CH_4 yr^{-1}, 112 Tg CH_4 yr^{-1} is emitted by rice agriculture and 189 Tg CH_4 yr^{-1} by ruminants (IPCC 2007a).

In California, agriculture accounts for 8% of all the anthropogenic GHG emissions (Figure 1.2). However, agriculture accounts for only 3% of CO_2 emissions. Agriculture-related emissions of CH_4 and N_2O are relatively much larger, and account for a total of 5% of California's emissions (Figure 1.3). In intensively managed agricultural systems, such as those of California, most of the agricultural GHG emissions are from non-CO_2 sources such as N_2O from soil (44%), and CH_4 emissions from rice paddies and enteric fermentation (16%). Emissions through the decomposition of plant residues are assumed to be negligible, since it is assumed that most soils are in equilibrium.

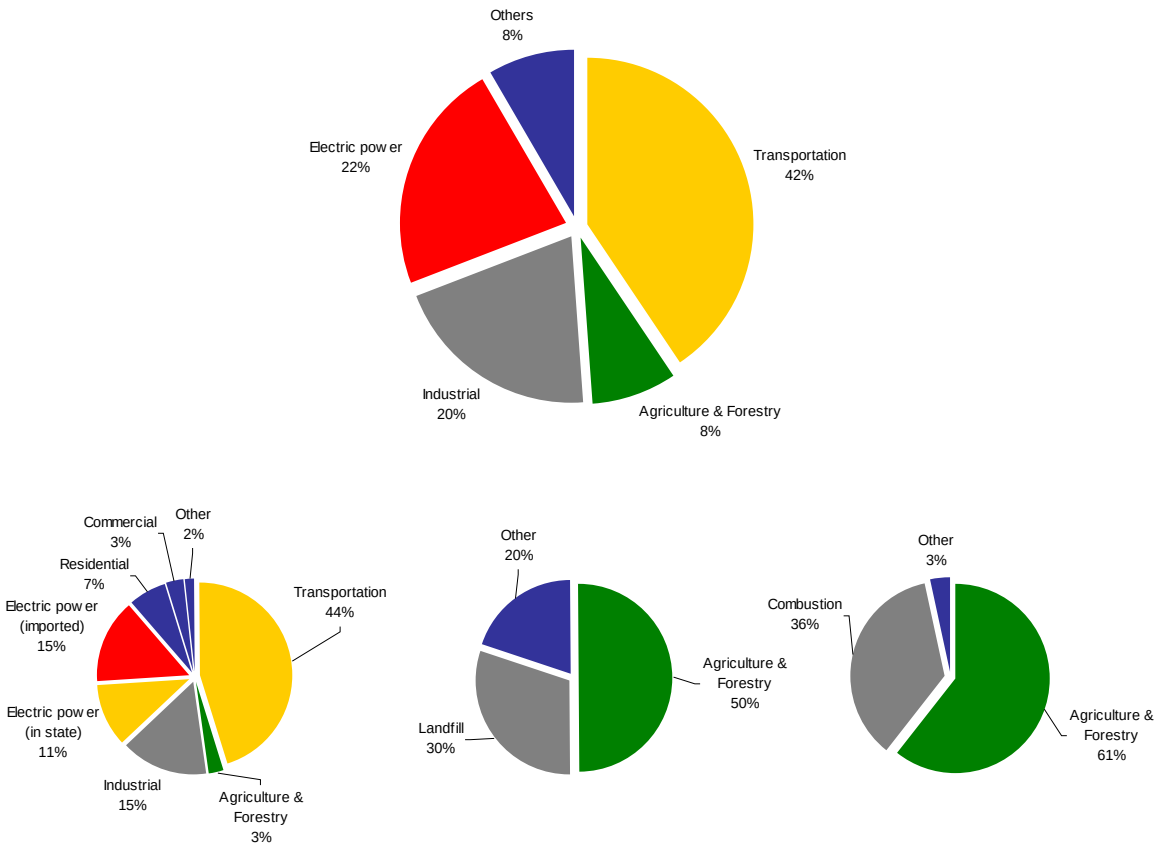

Figure 1.2. Relative importance of sources of greenhouse gases in California for 2004
Source: California Energy Commission 2006

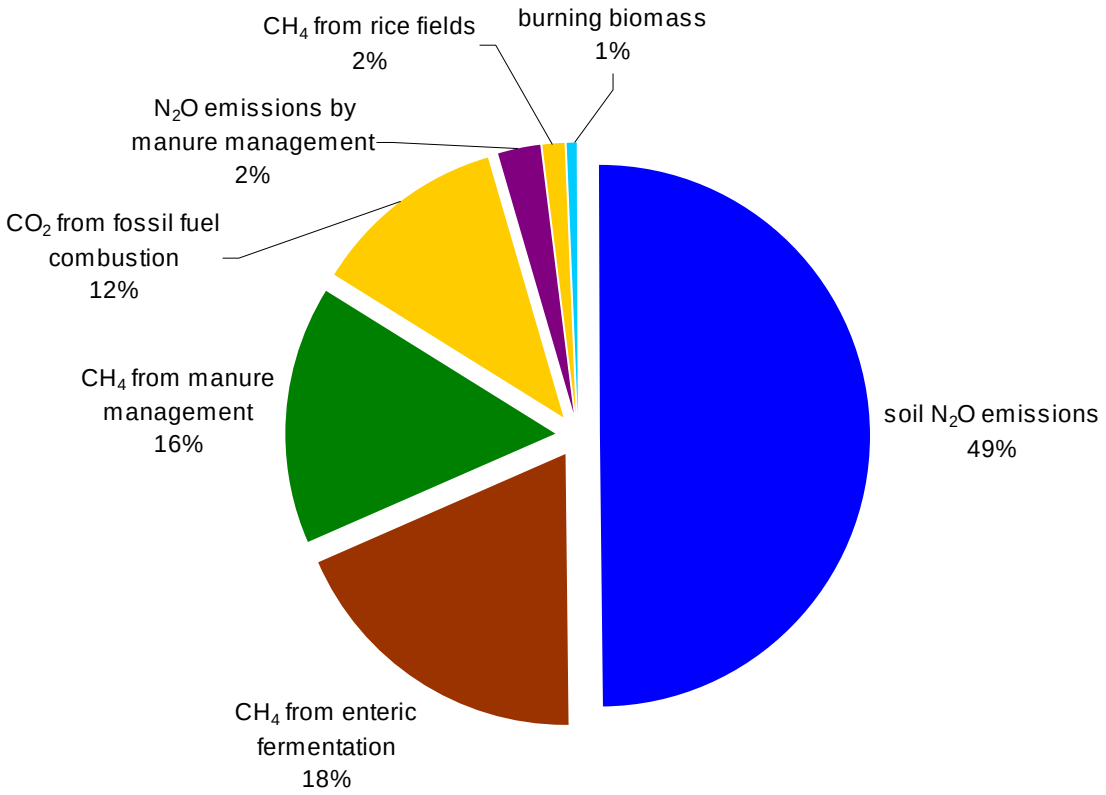

Figure 1.3. Relative sources of GHG emissions in California agriculture and forestry
Source: Adapted from California Energy Commission 2006

1.2. Demarcation of Terrestrial GHG Mitigation Options

There are five strategies for GHG mitigation attributed to terrestrial activities.

- Soil carbon sequestration through increases in soil organic matter.
- Reduction of N_2O and CH_4 emissions by agricultural soils.
- Reduction of fuel consumption by the agricultural industry.
- Carbon emission reductions from eroded sediments.
- Conversion of land to forest or grassland.

As pointed out by Brown et al. (2004), the high productivity of California agricultural land makes the policy of displacing agricultural land with afforestation unlikely. In addition, there has been an intensive scientific debate about whether erosion in fact leads to a net C sink or source (Stallard 1998; Jacinthe et al. 2004; Lal et al. 2004; Berhe et al. 2007; Ito 2007; Van Oost et al. 2007). Recent studies show that the effect of erosion on the global C cycle is likely minor and less significant than previously assumed (Van Oost

et al. 2007). Therefore, in this study, the focus lays on the first three aforementioned GHG mitigation strategies.

A recent study by Li et al. (2004) for the California Energy Commission used the Denitrification-Decomposition (DNDC) model (Li et al. 1992) in a simulation exercise to perform a preliminary evaluation of crop C sequestration and GHG emissions in California. The study concluded that through alternative management practices, agricultural soils in California have the potential for mitigating GHG emissions. The uncertainty in the predictions, however, was substantial.

This investigation focuses on annual crops. The carbon sequestration potential for deep-rooting crops or biofuel crops was not calculated, as little data is available to validate model results. Li et al. (2004) recommend evaluating conservation tillage and cover cropping for their potential in reducing greenhouse gas emissions. In addition, organic agriculture and reduction of N fertilization were included in the list of alternative management practices. The following list includes the alternative management practices evaluated in this report.

- Reducing tillage intensity.
- Cover cropping.
- Organic fertilization (organic agriculture).
- Reducing N fertilization (low input agriculture).

1.2.1. Reducing Tillage Intensity

Alternative tillage practices, which reduce the overall tillage intensity, are one of the best known management practices leading to increases in SOC and hence C sequestration (Follett et al. 2001; Smith and Conen 2004). However, there exists a wide variety in alternative tillage management practices, and therefore it is necessary to clearly define these practices beforehand. Systems without any form of tillage or soil cultivation are *no-tillage* or *zero-tillage* systems. These are hardly ever practiced in California. Systems in which tillage disturbance is reduced compared to conventional practices are referred to as *reduced tillage*, *minimal tillage*, *mulch tillage*, *ridge tillage*, or *conservation tillage*. Reduced or minimal tillage systems are defined based on the number of tillage passes, while conservation or mulch tillage systems are defined by the relative soil area covered by crop residues left non-incorporated on the field surface after harvest. The U.S. Department of Agriculture (USDA) Natural Resources Conservation Service and the University of California Conservation Tillage workgroup recently conducted a survey project in which they defined reduced tillage in California as "A tillage system using 40% fewer total passes than the number of passes in the conventional system for that crop, when all passes of equipment are included." For conservation tillage, typically 30% or more of the soil surface is covered with crop residues outside of the growing season. Conservation tillage practices are widespread in the United States. In 2002, 37% of the cropped soil surface of the United States was managed under one of these systems. Alternative tillage systems have many benefits apart from sequestering C in the soil,

including the reduction of soil erosion by water and wind, the conservation of soil organic matter and soil structure, and the prevention of evaporative water loss.

Experimental and modeling studies have predominantly focused on C sequestration through increasing soil C after adoption of reduced tillage (Eve et al. 2002; Falloon et al. 2002; Rickman et al. 2002; Six et al. 2004). Estimates of carbon sequestration for reduced tillage in these studies range from 200–600 kilograms of carbon per hectare per year (kg C ha^{-1} yr^{-1}) (Lal et al.1997); the U.S. Department of Energy estimates a sequestration rate from reduced tillage of about 300 kg C ha^{-1} yr^{-1}. Based on these numbers, studies like the Baseline, Classification, Quantification and Measurement for Carbon Market Opportunities in California project concluded that conservation tillage practices have great potential for sequestering carbon in the state. However, more recent studies have shown that these alternative tillage practices can actually increase the emission of other GHGs, outweighing the beneficial effects of increases in soil C. For example, Six et al. (2004) reported that shortly after the reduction of tillage intensity, GWP increases due to higher N_2O fluxes relative to conventional practices. It is only after longer-term adoption (> 10 years) of reduced tillage that a significant reduction in GWP in humid climates can be observed. Consequently, emissions of N_2O are the driving force behind much of the trend in net GWP in reduced tillage systems.

1.2.2. Cover Cropping

A cover crop is a crop that is primarily grown not for its commercial value, but rather for ancillary benefits. In California, cover crops are grown during the winter when sufficient rainfall is available. A cover crop is usually not harvested, but is sprayed down and/or incorporated into the soil at the end of its growing period. Ancillary benefits of cover crops include reduced soil erosion, weed growth suppression, attraction of beneficial insects, C sequestration through increases in soil C, and enhanced productivity of subsequently cultivated crops. Legumes are commonly chosen as cover crops because of their ability to bring nitrogen into the soil through nitrogen fixation. Next to legumes, also small grains such as oat, winter wheat, barley, triticale, hairy vetch, or winter rye are used as winter cover crop species. Their seeds are less expensive than those of legumes, but they do not grow that well during fall and winter. In this study, the focus is on the most widely used practice: legume cover crops grown during the winter.

1.2.3. Organic Fertilization

The National Organic Standard Board defines organic farming as an ecological production management system that promotes and enhances biodiversity, biological cycles and soil biological activity. It is based on minimal use of off-farm inputs and on management practices that restore, maintain, and enhance ecological harmony. Organic farming systems promote the use of renewable resources and enhance the ecological balance of natural systems. Organic residues (mostly manure) are used as fertilizer and no synthetic pesticides are used. Alternative weed control, often hand weeding, is used in the place of chemical herbicides, which drastically increases labor costs. Often, high soil disturbance through tillage is used to suppress weed growth.

In the United States, about 12% of all N fertilizer is applied as manure (Bouwman et al. 2002). The application of manure generally increases soil organic C contents. However, when manure is added to cropland at the same N application rates as mineral fertilizer, greater N_2O emissions have been observed from manure than from mineral fertilizer treatments in some situations, probably due to the readily available manure C added to the soil (Goodroad et al. 1984; Dong et al. 2000; Bouwman et al. 2002; and Stehfest and Bouwman 2006). Nevertheless, optimized manure management could decrease N_2O emissions associated with this practice. For the present study, the application rates of N were equal in organic systems and systems using mineral fertilizer.

1.2.4. Reducing Nitrogen Fertilization

According to IPCC (2007b), the most effective way to reduce GHG emissions in intensive agricultural systems is through minimization of N surpluses. This strategy might be especially relevant in California, where research indicates that emissions might be considerably higher due to high N fertilizer inputs and intensive irrigation (Ryden and Lund 1980). In California's input-intensive systems, over-fertilization is commonly practiced as an insurance against plant N deficiency and yield loss (Isfan et al. 1995). In these systems, the intensive use of fertilizer N and the frequent wetting and drying cycles induced by irrigation likely lead to great N losses through nitrification and denitrification. Moreover, N_2O losses are probably maintained at relatively high levels throughout the year due in part to the mild winter of California's Central Valley. However, quantification of these high losses has not been done for many of the cropping systems in California.

In this study, the general term *low-input agriculture* is used to refer to a system in which N fertilizer is reduced, typically by 25%. In the first years after conversion to a low-input system, enough residual nitrogen might still be available to get high crop yields. However, after a few growing seasons, a nitrogen deficiency might become noticeable. Therefore, it is essential from a sustainability perspective that long-term nutrient deficiencies are investigated in low-input systems.

1.3. Demarcation of Cropping Systems Studied

California's agriculture is characterized by a high diversity of cropping systems. About 350 crops are produced on 87,500 farms in the state. Many of these crops are cultivated exclusively in California.

California's Central Valley is divided into the northern Sacramento Valley (0.7 million ha of agricultural land), and the southern San Joaquin Valley (1.9 million ha of agricultural land). The Sacramento Valley is cooler and has more precipitation from winter storms which sweep down from the Pacific Northwest region. The most important cropping systems are orchards, rice, hay, and wheat. The San Joaquin Valley is warmer and drier (at some parts even desert-like) and dominated by orchard, cotton, and vineyard cropping systems. Due to the differences in climate, soils, and agricultural management, it is important to include both of these regions.

In this study, the most important crops in the state, both in terms of area cultivated and revenue generated (Table 1.2) were included, while omitting orchard-based systems, as virtually no data is available on orchards to validate the biogeochemical models. To calculate the biophysical potential, the following crops were included: hay crops (which mainly consist of alfalfa), cotton, flooded rice, vegetable production systems, small grains (wheat, oats, and barley), tomatoes, and corn/sorghum. These crops were analyzed in their typical rotations. For this reason, sunflower and melon were also added as crops commonly grown in a rotation with the previously mentioned crops. By limiting this study to these crops, about 60% of the land under crop production was taken into account (4.3 million acres out of a total 7.1 million acres).

Table 1.2. California's 10 most important crops in area cultivated and revenue generated

Area rank	Crop	Area (ha)	Revenue generated ($million)	Economic rank
1	hay (primarily alfalfa)	627,000	1141	6
2	nuts (almonds, walnuts, and pistachios)	364,000	3454	1
3	grapes	324,000	3166	2
4	cotton	266,000	625	11
5	rice	213,000	408	13
6	intensely cropped vegetables (lettuce, broccoli, carrots, etc.)	201,000	2920	3
7	wheat	149,000	104	>15
8	fruit trees (oranges, plums, lemon, and peaches)	145,000	1292	5
9	tomatoes	124,000	942	9
10	corn	45,000	52	>15

Source: CDFA 2006

1.4. Challenges in Evaluating the Economic Potential of Carbon Sequestration

A number of challenges exist in the evaluation of the economic potential for C sequestration in California. As discussed, due to the high diversity of California agriculture, statewide analyses of the biophysical potential and economic relevance of alternative management practices for GHG mitigation require farm-level analyses. In addition to this logistical challenge, other, more conceptual biophysical and economic barriers to a carbon credit system still exist and must be resolved in order to apply the system to agriculture. The primary economic barriers (permanence, verification, and uncertainty) are briefly discussed below. Other economic barriers to carbon trading (such as leakage or additionality) also exist, but these are not within the scope of this

project. See Winiwarter and Rypdal (2001) and Smith et al. (2007) for a more in-depth analysis of those issues.

1.4.1. Permanence

The mitigation benefits of an alternative management practice are greatest if they are permanent—that is, the benefits are maintained even if the alternative practice is abandoned. This is hardly ever the case with practices that focus on mitigation through soil C sequestration because a change in management most often reverses the gain in soil C. Furthermore, soil C will reach an equilibrium level after which there is no mitigation potential, but the alternative management must be maintained at the steady state (e.g., VandenBygaart et al. 2002; Six et al. 2004). If not, all the carbon that was stored in the soil system might be lost and converted back into atmospheric CO_2. Carbon sequestration in the soil is therefore only a buffer storage for atmospheric CO_2. In contrast, management practices that focus on reductions in N_2O emissions are permanent, because N that is not added to the soil will never be converted to N_2O, regardless of the subsequent management.

1.4.2. Verification

Critical to the development of a carbon-trading effort is verification. A carbon credit system must have the capacity to ensure that GHGs were effectively mitigated. This requires a measurement of GHG emissions under the alternative management, as well as an estimate of the baseline GHG emissions. However, it remains extremely costly to measure the exact amount of farm-level GHG mitigation through adoption of an alternative management practice. For the trace gases CH_4 and N_2O, this would require a continuous monitoring of trace gas exchange with the atmosphere (Smith et al. 2007). The analytical equipment needed is expensive and labor-intensive, therefore, this option is not cost-effective. Measurement of changes in soil C stocks is easier, as it requires only two measurements (before and after the adoption of the management practice). However, these measurements are still too expensive, which makes a field-by-field measurement of the amount of carbon stored not cost-effective at this point. In addition, measurement protocols are still under development and lack standardization. Until a practical means of verifying emissions is established, carbon sequestration programs should be based on payments for the adoption of the alternative practices themselves (Mooney et al. 2004). In addition, agronomic process models simulating trace gas exchange under different land uses and management practices are currently recognized as the preeminent tool for establishing guidelines and incentives to reduce GHG emissions in agriculture.

1.4.3. Uncertainty

Every emission reduction potential is a prediction and is therefore inherently uncertain. In the context of emission trading, the risk that the actual mitigation will not occur is directly related to the uncertainty around the reduction potential. Therefore, a higher-risk reduction strategy will be much less valuable (monetarily and environmentally) than a lower-risk reduction strategy with a similar average biophysical sequestration

potential. Uncertainty can be reduced by increasing the geographical and temporal scope of carbon credit contracts. Multi-region, multi-year contracts will reduce the uncertainty of a GHG mitigation project (McCarl et al. 2007; Smith et al. 2007).

1.4.4. Transition Inertia

Although there might be significant biophysical potential to mitigation of GHG emissions in California agriculture, the question remains whether a productive sector will accommodate a carbon sequestration activity that requires participants to adopt new forms of management not yet widely practiced. Conventional agricultural practices have developed over decades and have proven to successfully maximize yields. It is precisely the popularity of intensive practices that makes it difficult to predict how an individual farmer will react to a credit system and whether he or she will adopt GHG mitigation management practices. This is a key piece of information needed in evaluating the cost-effectiveness of GHG mitigation policies. In addition, each of the alternative management options has different cost structures and relative profitability requirements that influence agriculture's overall effectiveness for GHG mitigation.

1.4.5. Difficulties in Integrating Co-Benefits

Advocates of carbon sequestration often argue that carbon sequestration practices have important co-benefits beyond just sequestering carbon. These co-benefits include a reduction in soil loss due to erosion, a reduction in nitrate and phosphorus leaching and subsequent groundwater eutrification, and landscape esthetics in the case of winter cover cropping. It has been suggested to value these co-benefits through some type of green payment program akin to the Conservation Reserve Program (CRP) or the Conservation Security Program (CSP). However, co-benefits cannot be disentangled in land under carbon-sequestering management. Integrating their value into a carbon credit system introduces fundamental difficulties for policy makers (Feng et al. 2005). Although co-benefits are of great importance in policy design, they are beyond the scope of this study.

1.5. Objectives

The overall goal of this study is to provide a complete accounting of land use and management impacts on C sequestration and trace gas emissions in California agricultural lands. This goal encompasses five main objectives.

- Evaluate, calibrate and validate ecosystem models for simulations of crop productivity, C storage, and trace gas fluxes in California agroecosystems.
- Integrate ecosystem models with economic models at the field and county levels.
- Produce regional projections for the biophysical potential and economic feasibility of C sequestration and reduction in trace gas emissions.
- Quantify uncertainties for the modeled C sequestration and reduction in trace gas emissions for the county-level results.

- Perform a preliminary assessment of the potential to mitigate greenhouse gas emissions for the California's Central Valley as a whole.

2.0 Calibration of the DAYCENT Model to Californian Conditions

2.1. Summary

This section discusses (1) calibrating and validating a biogeochemical model (DAYCENT) for conventional and alternative arable crop production practices in California's Central Valley, (2) estimating net GHG fluxes of CO_2, N_2O, and CH_4 from these systems, and (3) quantifying the uncertainty around model predictions induced by variability in the input data. Four field sites for which long-term measured data were available were used to address these goals: the Sustainable Agriculture Farming Systems (SAFS) project, the Long-Term Research on Agricultural Systems (LTRAS) project, Field 74 in the Southern Sacramento Valley, and the West Side Research and Extension Center (WSREC) experimental site in the Central San Joaquin Valley.

The range of alternative management options at these sites included cover cropping, organic practices, and conservation tillage. These were compared to conventional agricultural management. The DAYCENT model predicted yields and soil organic carbon levels adequately. In total, 86% to 94% of the measured variation in yields and 69% to 87% of the measured variation in SOC contents were modeled. The SOC contents at the SAFS and LTRAS sites were overpredicted by about 10%. Daily N_2O fluxes at the Field 74 experiment were predicted fairly well. The simulated variability (quantified using a Monte Carlo analysis) was generally smaller than measured variability, in particular for N_2O emissions.

Among the alternative practices evaluated, conservation tillage led to the smallest reductions in global warming potential: 0.17 ± 0.13, 0.33 ± 0.03, and 0.49 ± 0.12 Mg CO_2-eq ha^{-1} yr^{-1} at the LTRAS, WSREC, and Field 74 sites respectively. Cover cropping with winter legume crops led to a larger mitigation than conservation tillage: 1.16 ± 0.16, 2.71 ± 0.06, and 2.65 ± 0.04 Mg CO_2-eq ha^{-1} yr^{-1} at the LTRAS, SAFS, and WSREC sites, respectively. Organic practices led to the largest mitigation: 4.58 ± 0.16 Mg CO_2-eq ha^{-1} yr^{-1} (LTRAS). Annual differences (such as those in weather or management) contributed to more of the variance in annual GHG emissions (about 40%–90%), compared to the variance induced by soil variability. It was concluded that the DAYCENT model can simulate GHG emissions satisfactorily, but that a sound error analysis needs to accompany the analyses to understand the risks and potentials of GHG mitigation through adoption of alternative practices.

2.2. Introduction

Quantifying GHG exchanges at a regional scale requires ecosystem process models which take into account different cropping systems, soils, climates, and site managements. In the past, such models have been used successfully to predict changes in soil C and trace gas fluxes at the plot and landscape scale (Paustian et al. 1997; Del Grosso et al. 2006). Nevertheless, the success of these models is strongly dependent on

whether they were calibrated for the specific local conditions of the systems under investigation. In a comparative analysis of nine different ecosystem models using validation data from seven long-term field sites, Smith et al. (1997) concluded that model performance was strongly dependent upon (1) whether the models were developed for soils and conditions similar to the tested field sites, and (2) how well they were calibrated for the site studied. For example, Campbell et al. (2001) concluded that both EPIC and CENTURY, two commonly used ecosystem models, were unable to satisfactorily predict the long-term SOC changes of different management practices in southern Saskatchewan conditions when no site-specific calibration was conducted.

Typically, results from biogeochemical models are presented without quantification of the uncertainty around their estimates. Nevertheless, valid inferences are not possible without an estimate of the accuracy of predictions. Every simulated value requires a quantification of the associated error (Ogle et al. 2006). This error originates from variation within the input data or from the limited representation of the mechanisms within the model (Ogle et al. 2006). The first source of uncertainty is classically quantified by performing multiple model runs while slightly varying input variables. For example, in a Monte Carlo analysis, a large number of simulations is carried out in which the input variables are varied randomly based on their probability density function (Saltelli 2000). The second error is assessed by confronting modeled and measured data.

This section focuses on (1) calibrating and validating the DAYCENT model for California conditions using conventional and alternative management practices, (2) estimating net GHG fluxes in these agroecosystems, and (3) quantifying the uncertainty around model predictions due to variability within the input data.

2.3. Materials and Methods

2.3.1. Model Description

The DAYCENT model is a version of the well-known CENTURY ecosystem model (Parton et al. 1987; 1994; Metherell et al. 1995) which uses a daily time step. DAYCENT was developed to simulate ecosystem C and nutrient dynamics and trace gas fluxes. It includes submodels for nitrification and denitrification (Parton et al. 1996; Del Grosso et al. 2000), CH_4 oxidation (Del Grosso et al. 2000), and soil water and temperature (Parton et al. 1998). It is a fully resolved ecosystem model simulating the major processes that affect SOM, such as plant production, water flow, nutrient cycling, and decomposition. The model simulates SOC and N stocks, which are represented by two plant litter pools and three SOM pools (termed *active, slow,* and *passive*). These SOM pools are explicitly defined by their turnover time: one to five years for the active pool, 20 to 40 years for the slow pool, and 200 to 1500 years for passive SOM. Nutrient fluxes between pools are further controlled by rate modifiers dependent on moisture, temperature, soil texture, and soil tillage. The crop sub-model simulates crop growth, dry matter production, and yield to estimate the amount and quality of residue (that is, C and N inputs) returned to the soil. It also simulates plants' influences on the soil micro-environment (water and

nutrients). The crop sub-model simulates phenology, plant tissue C-to-N ratios, C allocation between roots and shoots, and growth responses to light and temperature. A variety of management options may be specified, including crop type, tillage, fertilization, organic matter (e.g., manure) addition, harvest (with variable residue removal), drainage, irrigation, burning, and grazing intensity.

2.3.2. Sites Descriptions

Four long-term agricultural research experiments were identified that were appropriate for the calibration of DAYCENT. Table 2.1 summarizes the crop rotation sequences for these experiments.

Table 2.1. Rotation sequences for four long-term field experiments in California. Crops in between brackets are grown in the fall and winter season. Sequences were repeated continuously, except for the Field 74 experiment, which lasted three years.

			Year 1		Year 2		Year 3		Year 4	
Site	**Treatment**	**W**	**S**	**W**	**S**	**W**	**S**	**W**	**S**	**W**
LTRAS	conventional		tomato		corn		-	-	-	-
	cover-cropped		tomato	(CC)	corn		-	-	-	-
	organic		tomato	(CC)	corn	(CC)				
SAFS	conventional – 4		tomato		safflower		corn	(wheat)	bean	
	conventional – 2		tomato	(wheat)			-	-	-	-
	cover-cropped		tomato	(CC)	safflower	(CC)	corn	(CC)	bean	(CC)
WSREC	conventional		tomato		cotton		-	-	-	-
	cover-cropped		tomato	(CC)	cotton	(CC)	-	-	-	-
Field 74	conventional	(wheat)	corn		sunflower		chickpea			

Note: S = spring and summer season, W = fall and winter season, LTRAS = Long-Term Research on Agricultural Systems, SAFS = Sustainable Agriculture Farming Systems, WSREC = West Side Research and Extension Center, CC = cover-cropped

LTRAS

The Long-term Research on Agricultural Systems (LTRAS) project[2] is an ongoing, long-term field experiment established in 1993 to study the sustainability of irrigated Mediterranean cropping systems under conventional and alternative managements. It is located on 28.8 ha of land near Winters, California (38°32′3″ N, 121°52′29″ W). Two soil types are present at the LTRAS site: (1) Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerothent), and (2) Rincon silty clay loam (fine, montmorillonitic, thermic Mollic

[2] See http://ltras.ucdavis.edu.

Haploxeralf). Clay contents vary from 8% to 19%, and sand contents vary from 17% to 27%.

LTRAS includes 10 cropping systems (treatments), but here only the three corn–tomato (*Lycopersicon esculentum* var. "Halley") rotations were considered. These three rotations are (1) a conventional management system (using chemical fertilizer and pesticides; CCT); (2) a system consisting of a legume cover crop preceding unfertilized corn and followed by conventionally fertilized tomato (LCT); and (3) an organic system with poultry manure amendments, no chemical fertilizer, and a legume cover crop grown in the winter each year (OCT). The experiment was completely randomized; each of these treatments was replicated three times on 0.4 ha plots. Each crop in the two-year system is present each year. Tomatoes grown under CCT and LCT are fertilized 45 kilograms of nitrogen per hectare (kg N ha^{-1}) at transplanting and 100 kg N ha^{-1} as a side-dress application. In the CCT system, corn received 45 kg N ha^{-1} pre-plant and 160 kg N ha^{-1} as a side dress. The cover crop used as a green manure in the LCT and OCT systems is sown as a mixture of 24% pea (*Pisum sativum* L.) and 76% common vetch (*Vicia sativa* L.) by seed weight. Initially, the CCT treatment used a corn variety that matured in approximately 185 days (Pioneer 3162), whereas the LCT and OCT treatments used a short season corn variety that is planted later and matured in approximately 150 days (NC + 4616). Since 2003, a single corn cultivar (ST 7570) has been used to accommodate direct comparisons between standard and conservation tillage subplots. Details of the experiment and yields from the first nine years of the experiment are presented in Denison et al. (2004). More recent results are reported in Kaffka et al. (2005) and Mitchell et al. (2007). Soil C data were collected for all plots at the inception of the trial in fall 1993, and occasionally thereafter (in 1995; 1998; 1999; 2003; 2004) (Kong et al. 2005). From 2003, each of the 0.4 ha plots were split into a standard tillage and conservation tillage half. Daily weather data was available from the on-site weather station.

SAFS

The Sustainable Agriculture Farming Systems (SAFS) project[3] was a large-scale field experiment at the Agronomy Farm of University of California at Davis (38°32′ N, 121°47′ W), conducted from 1989–2000. The experiment was established on a 8.1 ha site encompassing a Reiff loam (coarse-loamy, mixed, nonacid, thermic Mollic Xerofluvents;) and a Yolo silt loam (fine-silty, mixed, nonacid, thermic Typic Xerorthents). Soil texture ranged from a maximum of 18% clay and 58% sand to a minimum of 8% clay and 68% sand.

For three different cropping systems, sufficient input data was available for modeling purposes: (1) a conventionally managed system under a four-year rotation of tomato (var. Brigade) – safflower (*Carthamus tinctorius* L.) – corn – wheat (*Triticum aestivum* L.) – bean, and (2) a four-year cover-cropped system under the same crop sequence as the former system, but with legume cover crops preceding each summer crop and a two-

[3] See http://safs.ucdavis.edu.

year conventionally managed system under a tomato-wheat rotation. The cover crop was a mixed culture of oat (*Avena sativa* L.) and purple vetch (*Vicia benghalensis* L.), which was either harvested for hay or incorporated as a green manure. This annual variation was simulated in the model runs. Fertilizer applications varied throughout the experiment, which was represented in the simulations. Across all years, an average of 166 kg N ha^{-1} yr^{-1} was applied as fertilizer in the four- and two-year rotation conventionally managed treatments, compared to 42 kg N ha^{-1} annually in the cover-cropped treatment. Additional details of the experimental design are described in Clark et al. (1998). Soil C was measured in 1988, 1993, 1995, 1998, and 2000 (Doane et al. 2003, 2004). Daily weather data was available from the California Irrigation Management Information System (CIMIS) station at Davis.

WSREC

The University of California West Side Research and Extension Center (WSREC) experiment in Five Points, California (36°20′29″ N, 120°7′14″ W) was designed to quantify the interactions of tillage intensity and cover cropping on soil and air quality. The study was conducted on a 3.2 ha parcel of Panoche clay loam (fine-loamy, mixed, supernatic, thermic Typic Haplocambids). Clay contents within the study area ranged between 25% and 35%, and sand contents ranged between 35% and 51%. The field experiment had four tomato (var. "8892") – cotton (*Gossypium hirsutum* L. var. "Riata") rotations comparing standard and conservation tillage practices with and without winter cover cropping. The cover crop used was a mixture of 30% Juan triticale (*Tritosecal* Wittm), 30% Merced ryegrain (*Secale cereale* L.), and 40% common vetch (*Vicia sativa* L.) (by weight) planted in the beginning of November and chopped mid-March. The standard tillage systems used tillage operations representative of California row crops to break down and establish new beds in the fall of each year. The conservation tillage systems were managed to minimize tillage as much as possible, but included midseason cultivation within the furrows for tomato production and undercutting cotton after harvest. Within the conservation tillage system, beds have been maintained for the duration of the experiment, and field traffic and cultivation were restricted to furrows. In all treatments, cotton was fertilized with an initial 11 kg N ha^{-1} yr^{-1} and later side-dressed with 154 kg N ha^{-1} yr^{-1}. Tomato was fertilized with 11 kg N ha^{-1} yr^{-1} at the time of transplanting and later side-dressed with 137.5 kg N ha^{-1} yr^{-1}. A detailed analysis of operations in conservation and standard tillage systems is presented in Mitchell and Tu (2005). Daily weather data was available from the CIMIS station at Five Points.

Field 74

In 2002, a field experiment was established within a 32 ha agricultural field (38°36′ N, 121° 50′ W), to compare the effects of standard and conservation tillage on CO_2 and N_2O efflux from soils. Three soil series occur on the site: Myers clay (fine, montmorillonitic, thermic Entic Chromoxererts), Hillgate loam (fine, montmorillonitic, thermic Typic Palexeralfs), and San Ysidro loam (fine, montmorillonitic, thermic Typic Palexeralfs). The site has a shallow water table varying between 50–100 centimeter (cm) depth during

the rainy season from late autumn to early spring. Clay contents ranged from 11% to 29%, and sand contents range from 22% to 45%.

The field was split into two halves of 16 ha, and sampling points were established across the field using a uniform grid with 64 meter (m) spacing. Soil properties (such as sand, clay, SOC, bulk density) were measured at all sampling points in March 2004. Wheat was planted in the fall of 2002 and harvested in spring 2003. In 2004, corn (*Zea mays* L.) was grown. Ammonium nitrate (UAN-32) was applied initially at a rate of 50 kg N ha^{-1} and about 40 days later, UAN-32 was side-dressed at 150 kg N ha^{-1} yr^{-1}. In 2005, sunflower was grown, and fertilizer was side dressed at a rate of 90 kg N ha^{-1}. During the last year of the experiment (2006) chickpea was grown without fertilizer application.

Nitrous oxide fluxes were measured using chambers (Hutchinson and Livingston 2002) in 3 to 15 plots during 51 (standard tillage) or 50 (conservation tillage) campaigns from November 2003 to August 2006. At each sampling point, samples were taken from one to four locations representing spatial variability across the beds and furrows (i.e., middle of seed bed, side of seed bed, side of furrow, and middle of furrow). There was no consistent efflux pattern correlated with bed or furrow position, so fluxes were averaged at each sample location. Daily weather data was available from the CIMIS station at Davis. Rainfall data was available from a tipping bucket pluviometer on site.

2.3.3. Modeling Approach

Historical Runs

The three SOM pools used by DAYCENT are conceptual. Therefore, their relative size cannot be experimentally measured and historical runs were performed to initialize the size of these pools. These runs were divided into five periods: (1) native grassland (between 0 and 1869; run until equilibrium), (2) emergence of agriculture (between 1870 and 1920), (3) introduction of irrigation (between 1921 and 1949), (4) introduction of inorganic fertilizer (between 1950 and 1969), and (5) modern agriculture (from 1970).

The first four periods of management were assumed to be identical for all of the sites. For the first period, a medium-productivity grassland with a mixture of annuals and perennials was simulated, with a growing season from November until the end of April. Low-intensity cattle grazing was included. It was assumed that grazing affected 10% of the live shoots and 5% of the aboveground dead biomass. The simulation period (1870 years) was sufficient to attain equilibrium in all modeled C pools. The average modeled C input to the soil at equilibrium was 165 ± 13 grams of carbon per square meter (g C m^{-2}), which is 83% of the reported average C input values of around 200 g dry matter m^{-2} yr^{-1} (Bartolome and McClaran 1992; Valentini et al. 1995; and Potthoff et al. 2005). In the second period (the emergence of agriculture) a rain-fed low input winter wheat system with minimal disturbance of the soil and a fallow period every five years was simulated. In the third period (pre-modern agriculture) irrigation was introduced while the crops were gradually diversified to include summer-grown corn. In the fourth period, inorganic fertilizer was introduced. The increase in the amount of fertilizer used between 1950 and 1969 was simulated based on historical records of the USDA. During

this period, tomatoes were introduced, and the degree of soil disturbance was increased. In the last period, between 1970 and 1996, a random wheat – corn – tomato rotation with high-intensity soil disturbance was simulated. Similarly to the period before, the increasing use of fertilizer was simulated based on historical records. For every site, the local daily weather data from 1980–2000 were looped and used during the historical runs.

Calibration Procedure

First, the soil microclimate was verified against measured soil temperature and moisture contents (available at Field 74 and LTRAS). If necessary, parameters such as the saturated hydraulic conductivity, the volumetric water content at field capacity or wilting point, and the minimal soil water content, were adjusted. Secondly, the relative size of the live biomass compartments (roots, shoots, and harvestable part) was verified using published and measured root-to-shoot ratios, and harvest indices (ratio of harvestable part over total aboveground biomass). The C:N ratios of each of these compartments were verified with measured and literature values. These values were confirmed with model results from the Decision Support System for Agrotechnology Transfer (DSSAT)/California Environmental Resources Evaluation System (CERES) plant growth models, using average climate and soil conditions of Yolo County (Hoogenboom et al. 2004). Only after the modeled plant indices and ratios were correct, the photosynthetic rate parameter was adjusted to match the modeled harvestable biomass values with the recorded average yield data at the different sites. Once the live biomass was simulated correctly, the sizes of the dead biomass and litter layer compartments were checked and compared with measured data (LTRAS and Field 74) and literature values. If necessary, parameters controlling root or shoot death were adjusted. Next, soil C dynamics were verified. In addition, the simulated tillage intensity was adjusted until changes in soil C corresponded to those observed. Last, modeled N_2O fluxes were verified with measured data. This could only be done at Field 74, the only experiment for which daily N_2O fluxes were available. If necessary, specific parameters controlling soil moisture and parameters highly influencing N_2O production (such as the existence of soil water table and minimal volumetric soil water content per layer) were further adjusted.

Current Simulation and Calculations

All experiments were simulated from their date of establishment until the year 2006, except for the SAFS experiment, which was discontinued in 2000. Within each experiment, the net change in GWP with alternative management was calculated as follows:

$$\Delta \mathrm{GWP} = -\frac{44}{12} \times \Delta \mathrm{SOC} + 298 \times \Delta[\mathrm{N_2O}] + 25 \times \Delta[\mathrm{CH_4}], \qquad \text{[Equation 1]}$$

where $\Delta \mathrm{GWP}$ is the global warming potential in Mg CO_2 equivalents (CO_2-eq) ha^{-1} yr^{-1}, $\Delta \mathrm{SOC}$ is the simulated difference in soil organic C in Mg C ha^{-1} yr^{-1} (a positive value indicates an increase in SOC), $\Delta[\mathrm{N_2O}]$ is the simulated emission of N_2O in Mg N_2O ha^{-1}

yr^{-1}, and $\Delta[CH_4]$ is the simulated emission of CH_4 in Mg CH_4 ha^{-1} yr^{-1} (positive values indicate an increase in N_2O or CH_4 emissions). The 44/12 is used to convert mass of C to mass of CO_2, the 298 and 25 are the radiative forcing constants for a time horizon of 100 years according to the IPCC (2007a).

Uncertainty Estimation, Model Performance, and Statistical Analysis

For LTRAS, plot level information of soil properties and crop management was available for each separate field replicate (n=3). Therefore, each plot was simulated individually, and the standard deviation around the resulting estimated C and N fluxes of the different field replicates was reported. For the other field experiments, no data on individual field replicates was used, but only treatment averages and standard deviations. A Monte Carlo simulation approach was used for these sites to estimate variances for modeled results. A large number of input data files were generated by randomly varying input parameters simultaneously using univariate normal distributions with averages and standard deviations from measured data. The average and standard deviation of the modeled outputs were then calculated based on each of these input data files.

The total mean square error was divided into different components according to Gauch et al. (2003): non-zero intercept (squared bias), non-unity slope and lack of correlation. These components have distinct and transparent meanings. The non-zero intercept (squared bias) component represents the part of the total deviation due to a non-zero intercept in the relation between predicted and measured values; the non-unity slope component represents the part of the total deviation due to a slope difference; the lack of correlation component represents the contribution of the total deviation due to random scatter in both predicted and measured variates.

Annual emissions were analyzed with a mixed ANOVA model in which treatment, crop and tillage treatment (for LTRAS and WSREC), and their interactions were considered as fixed effects, and year was considered to be a random effect. In addition, year was also a repeated measurement variable with the plot replicate (at LTRAS) or the Monte-Carlo replicate (other sites) as subjects (Littell et al. 2006). The variance around annual emissions was partitioned by using the following model for individual GHG emissions:

$$Y_{ijk} = \mu + \alpha_i + w_j + \varepsilon_{ijk}, \qquad \text{[Equation 2]}$$

where Y_{ijk} is the annual GHG flux of treatment i, year j, and replicate k; μ is the overall mean (fixed effect); α_i the mean of treatment i (fixed effect); w_j the influence of season j (random effect, mainly caused by weather variations); and ε_{ijk} the residual of plot or Monte-Carlo replicate k (random effect). The average of treatment i over all years and plots ($\overline{Y_{i\bullet\bullet}}$) can then be expressed as:

$$\overline{Y_{i\bullet\bullet}} = \left(\mu + \alpha_i + \sum_{j=1}^{\#\text{years}} \sum_{k=1}^{\#\text{plots}} w_j + \varepsilon_{ijk} \right) \Big/ (\#\text{years})(\#\text{plots}) . \qquad \text{[Equation 3]},$$

The variance around the treatment mean becomes:

$$\text{var}\left(\overline{Y_{i\bullet\bullet}}\right) = \frac{\sigma_w^2 + \sigma^2 / \#\text{plots}}{\#\text{years}} , \qquad \text{[Equation 4]}$$

where σ_w^2 is the interannual variance, and σ^2 the residual variance. The proportion of the variance caused by interannual differences is then:

$$\frac{\sigma_w^2}{\sigma_w^2 + \sigma^2 / \#\text{plots}} . \qquad \text{[Equation 5]}$$

2.4. Results

2.4.1. Model Calibration

The crop parameters modeled were comparable with typical values from the literature (Table 2.2). Per crop and field site, average yields were predicted reasonably well (Figure 2.1), with variations explained by the model ranging from 86% to 94% (Table 2.3). In addition, SOC was predicted quite well (Figure 2.2), with variations explained by the model ranging from 69% to 87%, except for Field 74. Modeled yearly fluxes per crop were in the same order of magnitude as the yearly fluxes reported in the literature (Figure 2.4).

Table 2.2. Values of critical plant parameters for the seven crops modeled in this study. The first value is a literature value; the second value between brackets is the modeled value.

	beans		corn		safflower		sunflower		tomato		wheat		cotton	
C-to-N ratio of harvested AG biomass	10	[9]	30	[35]	18	[19]	14	[14]	22	[27]	22	[22]		[8]
C-to-N ratio of non-harvested AG biomass	15	[13]	60	[69]	38	[40]	40	[36]	24	[29]	90	[87]		[51]
C-to-N ratio of roots	13	[13]	55	[59]		[77]	76	[74]	41	[46]	34	[34]		[22]
harvest index	0.60	[0.61]	0.50	[0.53]	0.25	[0.27]	0.30	[0.30]	0.45	[0.53]	0.50	[0.50]	0.60	[0.60]
shoot-to-root ratio	4.5	[4.7]	4.3	[4.0]	4.0	[3.6]	6.6	[6.2]	4.2	[4.2]	4.5	[5.8]	5.1	[4.5]

Note: AG = aboveground

Table 2.3. Model performance statistics for predicted yields and SOM values for different treatments and four long-term field experiments in California. Definitions of the different partitions of the mean square deviation (MSD) are provided in the Uncertainty Estimation and Model Performance section of Section 2.3.3.

		LTRAS	SAFS	WSREC	Field 74
			Prediction of Yield		
Variation explained by model (%)		86	92	94	92
partitioning of the MSD	non-zero intercept (%)	13	0	1	4
	non-unity slope (%)	13	4	3	5
	lack of correlation (%)	74	96	96	91
			Prediction of Soil Organic Carbon		
Variation explained by model (%)		69	83	87	6
partitioning of the MSD	non-zero intercept (%)	6	23	6	27
	non-unity slope (%)	24	21	63	28
	lack of correlation (%)	70	56	31	45

For the LTRAS experiment, the model explained about 86% of the variation in measured yields, with most of this non-explained variation coming from the lack of correlation (74%), indicating that no large bias existed (Table 2.3). Even within a crop and across years and field plot replicates, yield predictions were accurate at this site (Figure 2.1). In addition, the modeled variability in yields was in the same range as the measured variability. The DAYCENT model accounted for 69% of the variations in modeled SOC. About 24% of the non-explained variation was due to a non-unity slope, indicating that SOC levels were slightly overpredicted at higher SOC levels (Figure 2.2).

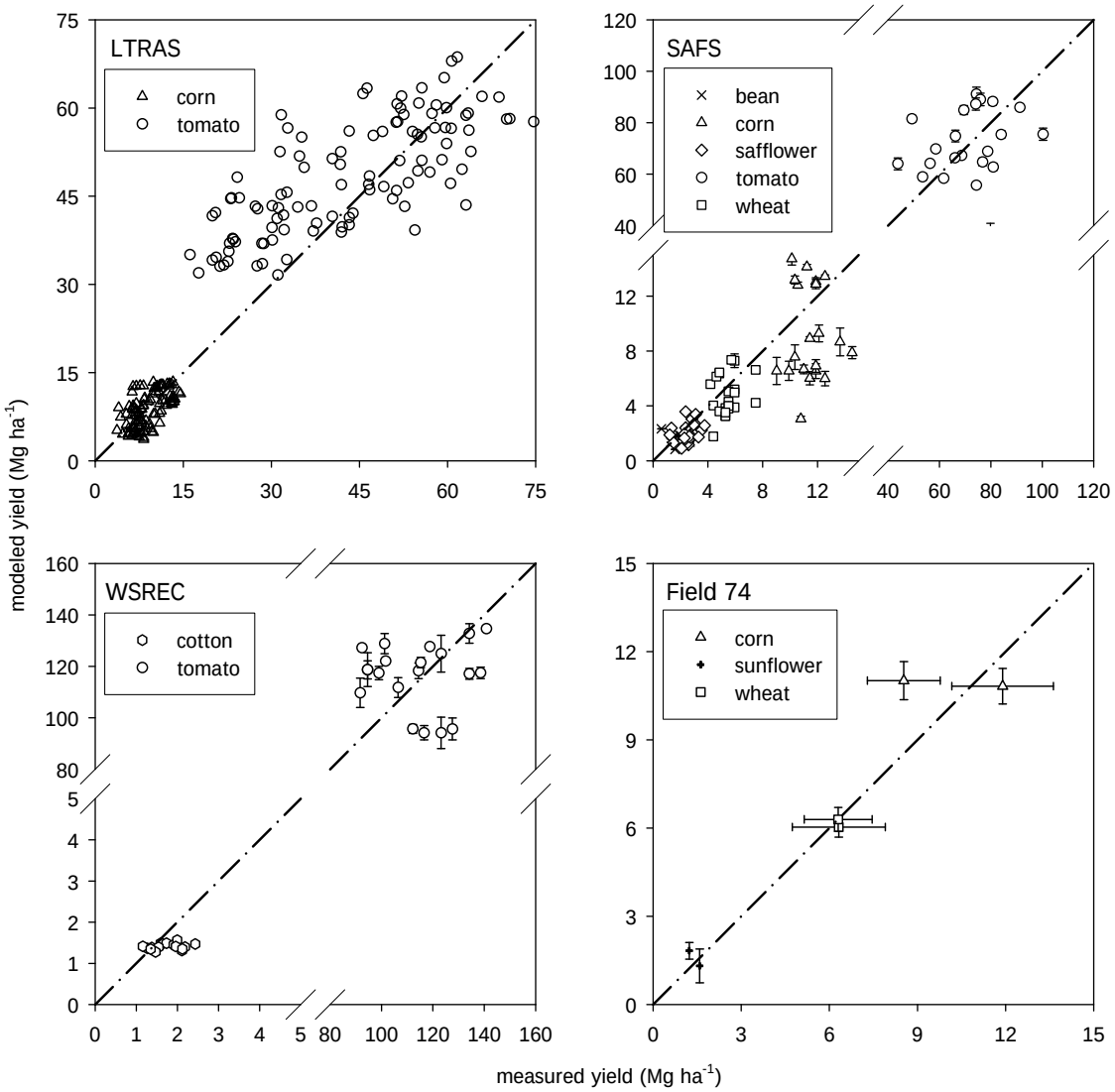

Figure 2.1. Modeled versus measured yields across various years, replicates, treatments, and crops at four long-term field experiments in California. For the Long-Term Research on Agricultural Systems (LTRAS) site, data per replicate plot was available and replicate plots were modeled separately. For the Sustainable Agriculture Farming Systems (SAFS) and the West Side Research and Extension Center (WSREC) sites, only averages per treatment were available. The vertical error bars show ± 1 standard deviation around modeled results, as calculated by a Monte Carlo analysis. For the Field 74 site, both average yields and yield standard deviations were available; these are indicated by a horizontal error bar, and the vertical error bar indicates ± 1 standard deviation based on a Monte Carlo analysis. The dashed line is the 1-to-1 line.

Table 2.4. Modeled annual N_2O emissions from four long-term field experiments in California and available literature data on N_2O emissions for five crops. Studies were selected that reported data which were measured during at least 300 days per year and where conventional fertilization practices were employed.

Modeled Data				Literature Data		
Crop	**Site**	**Modeled N_2O emission (kg N ha^{-1} yr^{-1})**		**Location**	**Measured N_2O emission (kg N ha^{-1} yr^{-1})**	**Reference**
corn	Field 74	4.1	± 0.7	Belgium	1.5	Goossens et al. (2001)
	WSREC	0.6	± 0.3	Germany	2.1	Mogge et al. (1999)
	LTRAS	3.0	± 0.1	Wisconsin, USA	3.6–5.2	Cates and Keeney (1987)
				Colorado, USA	4.0	Hutchinson and Mosier (1979)
				Costa Rica	7.1	Weitz et al. (2001)
				France	11.0	Jambert et al. (1997)
cotton	WSREC	3.6	± 0.2	Australia	1.6–2.6	Rochester (2003)
				Pakistan	3.6	Mahmood et al. (2000)
sunflower	Field 74	3.2	± 0.7	Germany	9.4–12.9	Flessa et al. (1995)
tomato	WSREC	4.4	± 2.1	Northern China	5.5	He et al. (2000)
	LTRAS	4.2	± 0.4			
	SAFS	2.1	± 0.4			
wheat	Field 74	1.3	± 0.2	Germany	0.7–1.2	Flessa et al. (1998)
	SAFS	1.9	± 0.5	Germany	1.0	Kaiser and Heinemeier (1996)
				Germany	3.5	Kaiser et al. (1998)

Note: LTRAS = Long-Term Research on Agricultural Systems, SAFS = Sustainable Agriculture Farming Systems, WSREC = West Side Research and Extension Center.

For the SAFS experiment, the model explained about 92% of the variation in yields; the 8% not explained came from the lack of correlation component (96%) (Table 2.3). The modeled variability in yields was in the same range as the measured variability (Figure 2.1). About 83% of the variation in SOC content was predicted by the model. Similar to the LTRAS experiment, the non-explained variation was partially due to a non-unity slope (21%). In addition, this was also caused by a non-zero intercept (23%). This indicates that SOC contents were slightly over-estimated both at small and larger SOC levels (Figure 2.2).

For WSREC, 94% of the variation in yield was modeled. Again, the non-explained variation was due to a lack of correlation (96%) (Table 2.3). The modeled uncertainties around the predicted yields were about three times smaller than the natural measured variation in yields among field replicates (0.5 Mg ha^{-1} compared to 1.5 Mg ha^{-1}, Figure 2.1). Generally, both modeled and measured variability in SOC contents were

substantial. The large variation in SOC levels explained was mostly due to a limited number of SOC measurements on cover-cropped treatments (Figure 2.2). In addition, the 30% increase in SOC due to conservation tillage in the cover-cropped treatments was not simulated (Figure 2.2).

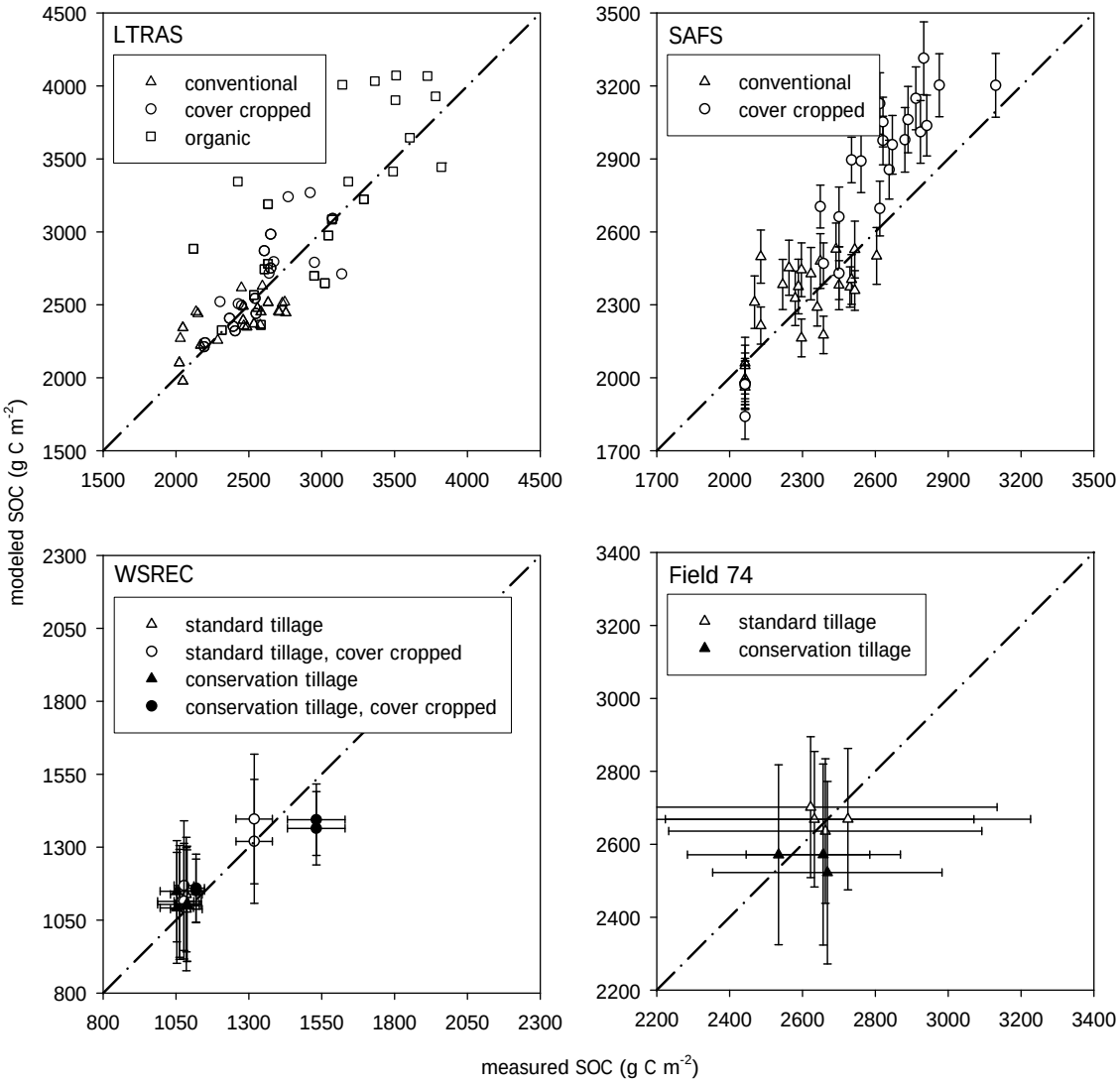

Figure 2.2. Modeled versus measured soil organic carbon levels across various years, replicates, treatments and crops at four long-term field experiments in California. For the Long-Term Research on Agricultural Systems (LTRAS) site, data per replicate plot was available which were all modeled separately. For the Sustainable Agriculture Farming Systems (SAFS) and the West Side Research and Extension Center (WSREC) sites, only averages per treatment were available, the vertical error bars show ± 1 standard deviation around modeled results, as calculated by a Monte Carlo analysis. For the Field 74 site, both average yields and yield standard deviations were available, which are indicated by a horizontal error bar, the vertical error bar indicate +- 1 standard deviation based on a Monte Carlo analysis. The dashed line is the 1-to-1 line.

For the Field 74 experiment, 92% of the variation in yield was modeled; of the non-explained variation, 91% was coming from a lack of correlation (Table 2.3). However, the measured variation in yields was larger than the uncertainty around the modeled yields (Figure 2.1). No differences in SOC were measured or modeled across seasons or treatments. Differences in means were well within the error range. Therefore, the portion of the variation explained was small (6%). Generally, the range in modeled average daily N_2O fluxes at the Field 74 experiment was comparable to the range in measured daily fluxes (Figure 2.3). The solitary N_2O emission peak measured on May 22, 2006, was not predicted by the model. In addition, the model underestimated N_2O emissions during May and June of 2004. The modeled variability around daily N_2O fluxes was smaller than the measured variability (Figure 2.3).

2.4.2. Simulated Greenhouse Gas Emissions and Mitigation Potentials

At the LTRAS site, SOC levels remained constant for the conventional treatment, while SOC levels in the organic and cover-cropped treatments increased substantially (Table 2.5) in both tillage treatments. Methane fluxes were similar among all treatments. The GWP was highest for the conventional treatment, followed by the cover-cropped and organic treatments in both standard and conservation tillage. Conservation tillage management, as established in 2003, led to a small but significant decrease in GWP (0.55 ± 0.13 Mg CO_2-eq ha^{-1} yr^{-1}). The cover- cropped system led to a net mitigation of 1.16 ± 0.16 Mg CO_2-eq ha^{-1} yr^{-1} compared to the conventional system. The organic system led to a net mitigation of 4.58 ± 0.16 Mg CO_2-eq ha^{-1} yr^{-1} compared to the conventional system. Interannual differences among GHG fluxes accounted for 40%–70% of the total variance.

For the SAFS experiment, the cover-cropped treatment sequestered about 0.6 Mg C ha^{-1} yr^{-1} more than the two-year and four-year conventional treatments, which did not differ from each other. The N_2O emissions increased in the following order: conventional two-year rotation, cover-cropped, and conventional four-year rotation. Methane fluxes were similar for the conventional four-year rotation and cover-cropped treatments, and smaller in the conventional two-year rotation. The GWP for the cover-cropped treatment was smallest of the three treatments. The GWP of the conventional four-year rotation was slightly larger than the conventional two-year rotation. Cover cropping led to a mitigation of 2.40 ± 0.06 Mg CO_2-eq ha^{-1} yr^{-1} compared to the conventional systems. About 90% of the variance of GHG emissions was caused by interannual differences.

In the WSREC experiment, adding a cover crop led to a much larger simulated increase in SOC (about 0.7 Mg C ha^{-1} yr^{-1}) than adopting conservation tillage (about 0.1 Mg C ha^{-1} yr^{-1}). Cover cropping did not change annual N_2O emissions in the standard tillage treatments, while it led to an increase in annual N_2O emissions of about 0.5 kg N ha^{-1} yr^{-1} in the conservation tillage treatment. Conservation tillage decreased GWP with 0.47 ± 0.03 Mg CO_2-eq ha^{-1} yr^{-1} averaged over the with-and-without-cover-crop treatments. Cover cropping led to a decrease in GWP of 2.64 ± 0.04 Mg CO_2-eq ha^{-1} yr^{-1} in both tillage treatments. About 85% of the variance of annual SOC differences and N_2O emissions

was explained by interannual differences, while this was only 38% for the variance of annual CH_4 emissions.

Table 2.5.Average differences in soil organic C (ΔSOC) (negative values indicate a decrease in soil C), N_2O and CH_4 emissions, and overall GWP (negative values indicate a net flux from the atmosphere to the soil) for each of the treatments of four calibration sites in California. Values are provided ± standard deviations.

Site	Treatment	ΔSOC (kg C ha^{-1} yr^{-1})	N_2O (kg N ha^{-1} yr^{-1})	CH_4 (kg C ha^{-1} yr^{-1})	GWP (Mg CO_2-eq ha^{-1} yr^{-1})
LTRAS	standard tillage	95	3.18	1.52	1.18
	cover-cropped and standard tillage	315	2.60	1.44	0.10
	organic and standard tillage	1324	3.02	1.49	-3.40
	(standard error)	(64)	(0.14)	(0.04)	(0.28)
	(% caused by interannual differences)	(74%)	(37%)	(46%)	(72%)
	(standard error of the difference)	(41)	(0.11)	(0.03)	(0.16)
	conservation tillage	47	3.01	1.51	1.27
	cover-cropped and conservation tillage	321	2.21	1.46	-0.10
	organic and conservation tillage	1279	2.98	1.49	-3.26
	(standard error)	(94)	(0.18)	(0.05)	(0.43)
	(% caused by interannual differences)	(65%)	(53%)	(68%)	(61%)
	(standard error of the difference)	(71)	(0.17)	(0.04)	(0.37)
SAFS	conventional 4-year rotation	407	2.2	1.6	-0.42
	conventional 2-year rotation	436	1.5	1.4	-0.84
	cover-cropped	998	1.7	1.6	-2.82
	(standard error)	(77)	(0.09)	(0.02)	(0.29)
	(% caused by interannual differences)	(94%)	(80%)	(89%)	(96%)
	(standard error of the difference)	(21)	(0.04)	(0.01)	(0.08)
WSREC	standard tillage	-90	4.0	2.0	2.25
	standard tillage, cover-cropped	677	4.0	1.9	-0.56
	conservation tillage	-9	3.3	2.0	1.61
	conservation tillage, cover-cropped	729	3.8	1.9	-0.85
	(standard error)	(38)	(0.10)	(0.03)	(0.15)
	(% caused by interannual differences)	(91%)	(82%)	(38%)	(92%)
	(standard error of the difference)	(14)	(0.06)	(0.02)	(0.04)
Field 74	standard tillage	128	2.6	1.5	0.79
	conservation tillage	256	2.4	1.3	0.23
	(standard error)	(27)	(0.12)	(0.06)	(0.13)
	(% caused by interannual differences)	(51%)	(49%)	(19%)	(43%)
	(standard error of the difference)	(22)	(0.09)	(0.09)	(0.12)

Note: CO_2-eq = CO_2 equivalents. LTRAS = Long-Term Research on Agricultural Systems, SAFS = Sustainable Agriculture Farming Systems, WSREC = West Side Research and Extension Center

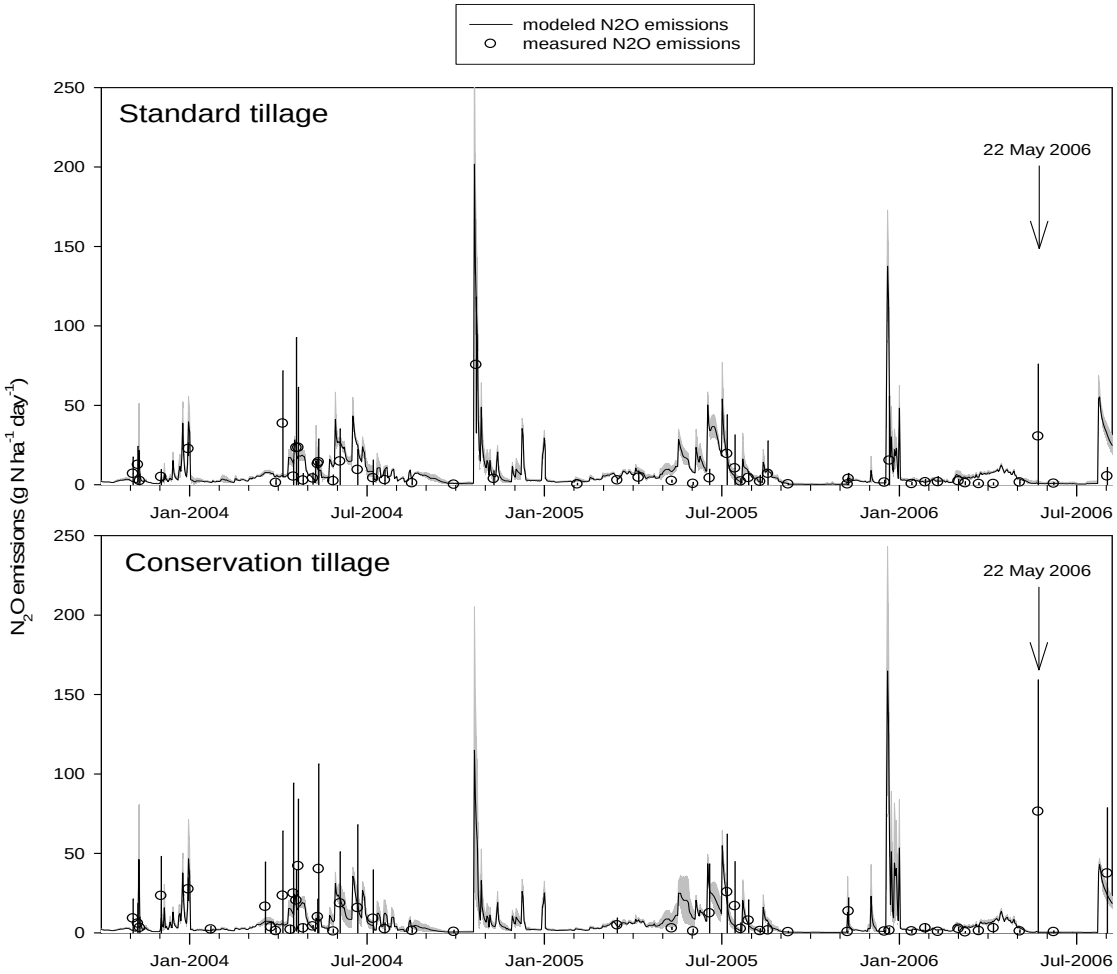

Figure 2.3. Modeled and measured N_2O emissions versus time for the conventional and conservation tillage treatments at the Field 74 experiment. The gray area around the model results shows ± 1 standard deviation around the average, as calculated by a Monte Carlo analysis.

At Field 74, a small increase in SOC in the conservation tillage treatment (about 0.1 Mg C ha^{-1} yr^{-1}) was simulated. In addition, both modeled annual N_2O and CH_4 fluxes were lower in the conservation tillage treatment compared to the standard tillage treatment. The GWP of conservation tillage was about 0.56 ± 0.12 Mg CO_2-eq ha^{-1} yr^{-1} less compared to the standard tillage treatment. Interannual differences explained about 50% of the variance of annual SOC differences and N_2O emissions and about 20% in annual CH_4 emissions.

2.5. Discussion

Changing land use and ecosystem management has been put forward as a way to mitigate increasing atmospheric GHG concentrations. Within agriculture, alternative management practices such as conservation tillage, winter cover cropping or organic

farming have been suggested as ways to mitigate GHGs. However, there is a large uncertainty around the values of GHG mitigation potentials, which strongly devalues the price of sequestered carbon and restricts the potential participation of agriculture in a carbon-credit market system. This uncertainty stems from the complex biogeochemical processes in the soil and rhizosphere leading to GHG emissions. These processes encompass nitrification, denitrification, and aerobic and anaerobic decomposition. They are influenced by an array of factors including climate, plant physiology, soil physical and biological properties and land use and management (e.g., crop type, irrigation, fertilization, cultivation, and residue management). Biogeochemical models can decrease this uncertainty by mechanistically simulating these processes. In addition, they can estimate potential changes in agronomic yields associated with these alternative management practices. However, before these models can be used, they should be soundly calibrated for local management, climate conditions and crop cultivars. Despite the economic importance of the agricultural industry in California, almost no data exist to calibrate such models. This is in part due to the great diversity of crops, cropping systems, microclimates, and soil conditions within the state. Still, carbon trading could form a substantial source of revenue for farmers within California. Therefore, an urgent need has emerged to collect data from agricultural experiments and employ these data to calibrate a biogeochemical model for California agriculture.

Data from four long-term field experiments were used to calibrate the DAYCENT model (Parton et al. 1996; Del Grosso et al. 2000). The calibration sites encompass a wide range of alternative management practices (standard and conservation tillage management, winter cover cropping and organic farming) and crops (beans, corn, cotton, safflower, sunflower, tomatoes, and wheat). The ultimate goal of this calibration exercise is to be able to simulate GHG emissions for annual systems within California's Central Valley. Therefore, modifications to model input files were kept as general as possible and not site dependent. For example, the parameterization for corn at the SAFS experiment was the same as corn from the conventional treatment at the LTRAS experiment. In addition, the same cover crop was used for all sites. However, this was not possible for all parameters. For example, the harvest index of tomatoes was different at LTRAS and SAFS in the Sacramento Valley than at WSREC in the San Joaquin Valley, due to the longer growing season in Fresno County where this experiment is located. In addition, the wheat harvest index used in Field 74 was notably smaller than reported literature values (0.37 versus 0.64). In these cases, all the other critical parameters were held constant, and only the relevant parameters were manipulated (e.g., harvest index maximum, or maximal rate of photosynthesis). Similarly, for the LTRAS experiment, a short-season corn cultivar was used in the cover-cropped and organic systems during the first 10 years of the experiment. To simulate this, minor modifications were made to our standard California corn cultivar.

Model parameters relating tillage to SOC decomposition were calibrated using data for the effects in tillage intensity derived from the various experiments. It was found that four different types of tillage events were necessary to simulate the variety of tillage

management in all the treatments and experiments considered: a conventional tillage pass, a conservation tillage pass, cover crop incorporation, and a within-season cultivation pass. For the standard tillage management, one conventional tillage event in the spring before planting, and one post-harvest was sufficient to simulate the observed changes in soil carbon. During the growing season, cultivation (mainly for weed suppression) was simulated using the within-season cultivation pass. To simulate conservation tillage management, one conservation tillage pass in the spring and one post-harvest sufficed (these were about 30% less intense than the conventional tillage passes). No within-season cultivation passes were scheduled in this management system. For cover-cropped treatments, one cover crop incorporation pass was scheduled in between the cover crop and main crop growing seasons. This pass should have only a minimal effect on decomposition.

For most crops and sites, average yields could be predicted well. In contrast, the standard deviations around measured yields (based on field replicates) were underestimated by the model (quantified in a Monte Carlo analysis). This was the case for corn and wheat crops in the Field 74 experiment and for cotton at the WSREC site, for which the standard error of simulated yields was about three times smaller than the observed standard error of cotton yields. This difference was attributed to several factors. First, a substantial amount of the factors that influence crop yield are not incorporated in the model (e.g., pests, seedling emergence problems, deficiency in micronutrients, temperature at anthesis, fruit set). Second, the Monte Carlo analysis did not take into account variations in management (such as fertilization amounts or exact planting or harvesting dates). Integrating this in an uncertainty analysis would be challenging since soil management is strongly correlated with weather, and such an integration is beyond this study's scope. Finally, some processes are naturally stochastic. For example, it is well known that the harvest index of water-stressed cotton is quite variable and unpredictable. The DAYCENT model is deterministic, and will therefore underestimate the variability associated with such a process.

Generally, simulated SOC values corresponded well with measured SOC values at different times and for the different treatments (variance explained ranged between 69% and 87%, except for the Field 74 site). The model overpredicted SOC levels with about 10% at the cover-cropped treatment of SAFS and organic treatment of LTRAS. Since the amount of C input to the SOC (plant residues and/ or manure) were modeled without bias, DAYCENT slightly underestimated SOC decomposition rates when C inputs were high. The variability of measured and simulated SOC values was substantial at Field 74 (coefficients of variation were about 25%). This was attributed to the well-known textural variability at this site (Lee et al. 2006), and the smaller size and non-replicated nature of this experiment compared to the other experiments. The model predicted that adopting conservation tillage led to an average increase in SOC of about 0.12 Mg C ha^{-1} yr^{-1} at LTRAS, 0.07 Mg C ha^{-1} yr^{-1} at WSREC, and 0.13 Mg C ha^{-1} yr^{-1} at Field 74. This is smaller than values reported in the literature. Franzluebbers (2005) reports values of 0.42 ± 0.46 Mg C ha^{-1} yr^{-1}, the review of West and Post (2002) reports a value of 0.6 ± 0.1

Mg C ha^{-1} yr^{-1}, and the review of Six et al. (2004) reports 0.2 Mg C ha^{-1} yr^{-1} for a 10-year-old no-tillage system in a humid climate. However, most of these numbers are based on systems where tillage is almost completely eliminated. In California systems, conservation tillage systems are still fairly intensive: the number of tillage passes is reduced from 10 to about 5. Compared to highly reduced tillage systems elsewhere, potential increases in SOC due to conservation tillage will be modest in California. Adding a cover crop during the winter led to an increase in SOC of 0.25 Mg C ha^{-1} yr^{-1} at LTRAS, 0.59 Mg C ha^{-1} yr^{-1} at SAFS, and 0.75 Mg C ha^{-1} yr^{-1} at WSREC. These values are close to the average SOC increase for no-tillage winter cover-cropping systems reported by Franzluebbers (2005) (0.53 Mg C ha^{-1} yr^{-1}) and are somewhat greater than the 0.1–0.3 Mg C ha^{-1} yr^{-1} range reported by Lal et al. (1998).

Comparison with literature values available showed that simulated annual N_2O fluxes are within the range reported by other authors (Table 2.4), and accounted for about 60% of the total GWP of the agricultural system. This value is close to the reported value of 50% for California cropping systems (Bemis et al. 2006. In addition, modeled average daily N_2O fluxes over time are within the range of measured values (Figure 2.3). This was not the case during the spring (May–June) of 2004 in the conservation tillage system during which the model underestimated N_2O emissions. This might be the result of an increase in bulk density and an associated decrease in pore space over time in the conservation tillage system (Lee et al. 2006). The DAYCENT model does not simulate compaction or loosening of the soil, and bulk densities are assumed to remain constant during the experiment. As a consequence, modeled N_2O emissions in this period were underestimated since they were based on a smaller bulk density than the actual value. The apparent variability of N_2O emissions was not accurately estimated using DAYCENT. This was attributed to the limited representation of the mechanisms involved in N_2O emissions within the model rather than an incorrect representation of the variability of the input data, which was elaborately characterized by Lee et al. (2006). A solitary peak of emission in the spring of 2006 (May 22), occurring in both the standard and conservation tillage treatments, could not be simulated. The measurement error around this peak was quite large (30 ± 46 and 76 ± 83 g N ha^{-1} day^{-1} in the standard and conservation tillage treatments, respectively). This peak occurred a day after a mild rain (7 millimeters) during the growth of the chickpea crop, to which no fertilizer was applied. Because the rainfall was very mild and occurred after a dry period of 20 days, DAYCENT could not model resulting short-term soil saturation conditions that trigger N_2O emissions.

The total mitigation potential of alternative practices was smallest for conservation tillage (0.47–0.56 Mg CO_2-eq ha^{-1} yr^{-1}), followed by cover cropping (1.23–2.63 Mg CO_2-eq ha^{-1} yr^{-1}) and the use of organic inputs (4.56 Mg CO_2-eq ha^{-1} yr^{-1}). However, not only the total mitigation potential is of interest, it is also important to know how much of the total reduction is attributed to increases in soil C versus reductions in N_2O fluxes. Namely, the capacity of a soil to store C is limited (VandenBygaart et al. 2002; Six et al.

2004), and if the proper soil management is not maintained, all or part of the sequestered C will be released again to the atmosphere.

In contrast, reductions in N_2O emissions are permanent (VandenBygaart et al. 2004; Smith et al. 2007). Although N_2O was typically the most important gas contributing to the total GWP, changes in soil C were key to achieving a negative GWP for mitigation potentials of alternative practices. For example, the cover-cropped treatment at LTRAS decreased the GWP by about 1.2 Mg CO_2-eq ha^{-1} yr^{-1}, but only about 26% of this reduction was due to reductions in N_2O fluxes. Similar contributions in decreases of N_2O fluxes to the total mitigation in GWP were observed for the other treatments and sites. At WSREC, however, winter cover cropping even led to an increase in N_2O emissions of about 0.5 Mg CO_2-eq ha^{-1} yr^{-1} in the conservation tillage treatments. Soil mineral nitrogen levels were higher for the cover-cropped treatments than the non-cover-cropped treatments during late spring (before planting) and during crop residue decay in the fall. The higher levels of soil mineral nitrogen caused higher nitrification and denitrification during these periods in the conservation-tilled, cover-cropped treatments.

Year-to-year differences in weather or management dominated the total variance around predictions of annual GWP. Consequently, an error analysis of predicted GHG mitigation potentials will have to take interannual variability into account. It can be expected that the error in estimating GHG mitigation related to interannual differences will decrease with the duration of the practice. Therefore, a sound quantification of this error is necessary to determine the contract duration and the risks associated with short-term versus long-term adaptation of alternative practices for mitigation of GHG emissions.

2.6. Conclusion

The ecosystem model DAYCENT was able to simulate average yields and GHG fluxes adequately under California conditions and managements, but that the model generally underestimated the variability around measured yields and emissions. This study's simulations suggest that that mitigation potentials increase across the range of management practices simulated, from conservation tillage to winter cover cropping to organic inputs (cover crops + manures). To extrapolate these results to a regional scale, it will be necessary to simulate GHG fluxes across a range of soils, land uses, and climates based on a calibrated model such as the one presented here. Such a simulation will also have to quantify the error around the predicted mitigation potentials. Within the limitations discussed here, the calibrated DAYCENT model can be used as a tool to forecast GHG fluxes in alternative California agroecosystems, but only when combined with a rigorous error analysis.

3.0 Assessing the Potential for Greenhouse Gas Mitigation in Annual Cropping Systems of California

3.1. Summary

The aim of this study was to model changes in yields and GHG emissions at a regional scale. Therefore, all unique crop rotation- weather- soil type combinations were modeled for the period 1997–2006 in 10 counties. Eight typical crops were included: alfalfa, corn, cotton, melon, rice, safflower, sunflower, tomato, and wheat. Each of these were cultivated in their typical rotations. All possible combinations of conservation tillage, winter cover cropping, and manure application were considered, together with a management option in which fertilizer N was 25% reduced and compared these to conventional management practices. The DAYCENT model simulated almost no decreases in yields for these management systems. Tomatoes and rice were most vulnerable, with yield reductions up to 5% for these crops. Changes in soil C and trace gas fluxes corresponded well to measured values in the literature. Potential reductions ranged from -0.7 to -3.3 Mg CO_2-eq ha^{-1} yr^{-1} in the Sacramento Valley and -0.5 to -2.5 Mg CO_2-eq ha^{-1} yr^{-1} for the San Joaquin Valley. Although the effects of the single management options on potential GHG reductions were modest (around -1 Mg CO_2-eq ha^{-1} yr^{-1}), combining these led to significant decreases in GHG emissions (up to about -3 Mg CO_2-eq ha^{-1} yr^{-1}). Particularly the combination of winter cover cropping with manure application was efficient in reducing GHG emissions. The combination of winter cover cropping, manure application, and reduce tillage was not regarded practically feasible. Most of these reductions in emissions (60%–80%) were attributable to increases in soil C, and therefore not permanent. Although a 25% reduction in fertilizer application caused only a modest decrease in emissions (-0.75 Mg CO_2-eq ha^{-1} yr^{-1}), most of this reduction (> 95%) was due to decreases in N_2O emissions, which are permanent. Due to the large inherent variability of these potentials, it was concluded that contracts over many fields will be necessary to minimize the variability around GHG emission reduction and the resulting carbon credit discounts.

3.2. Introduction

The previous section reported the results of the calibration of the DAYCENT model (Del Grosso et al. 2006) for Californian conditions using data from several long-term field experiments. This calibrated model can now be used to calculate potential mitigation at a regional scale. Both the county level and the watershed level were considered in this study.

Eight counties (about 0.7 million ha agricultural land) from the Sacramento Valley and two counties (about 0.6 million ha agricultural land) from the San Joaquin Valley were thus included in the present study. The counties studied include Butte, Colusa, Glenn, Sacramento, Solano, Sutter, Yolo and Yuba in the Sacramento Valley, and Kings and Fresno in the San Joaquin Valley (see Figure 3.1).

Figure 3.1. Position of the 10 counties that were analyzed for this study

Most modeling studies have looked at individual years. If a longer period is simulated, crops are usually simulated in monoculture. However, in California, crops are almost always grown in complex rotations. This is mainly to improve soil fertility and reduce pests. It is rare that most crops are grown in monoculture. Only rice cropping systems are commonly grown consecutively. This makes a model calculation of the potential GHG emission reductions much more complex. Potential reductions should not be calculated per crop but per crop rotation. There are many more possible crop rotations than there are individual crops.

The current conventional practices (tillage intensity, fertilizer amounts) have been developed over several decades, and they have been adjusted to maximize yields. The proposed alternative management practices have a dual goal: maximizing yield while minimizing GHG emissions. The long-term effects on yields and GHG emissions are unknown. It is therefore essential to simulate the impact of these alternative management practices over a longer period. It has been repeatedly reported that yield declines or that changes in nitrous oxide emissions only become apparent in the long run (Six et al. 2004). A sound analysis of the potential mitigation of various strategies should therefore be carried out over a longer time period.

This study's used a biogeochemical model to quantify the medium-term (10-year) change in crop yields and GHG emissions that could occur by changing conventional agricultural practices to alternative practices for 10 counties in California's Central Valley. The crops are considered in their typical rotations. The alternative practices considered include reduced tillage, winter cover cropping, organic practices, and reduced fertilizer input.

3.3. Materials and Methods

3.3.1. Regional Extent

Counties considered in this calculation were chosen based on the county-level economic importance of annual field crop agriculture. Most management data was available through the University of California Extension Service. Annual cropping systems comprise about 64% of the agriculture in these counties, with the main crops (descending in importance of surface area) including rice, alfalfa, cotton, tomatoes, (winter) wheat, corn, other vegetables, safflower, and barley (see Figure 3.2) (USDA 2002). Main perennial systems include fruit and nut orchards and vineyards, but they were not considered in this study.

3.3.2. Model Description

For an in-depth description of the DAYCENT model, see Section 2.

3.3.3. Input Data

The most detailed input data available at the county scale was used (see Figure 3.3).

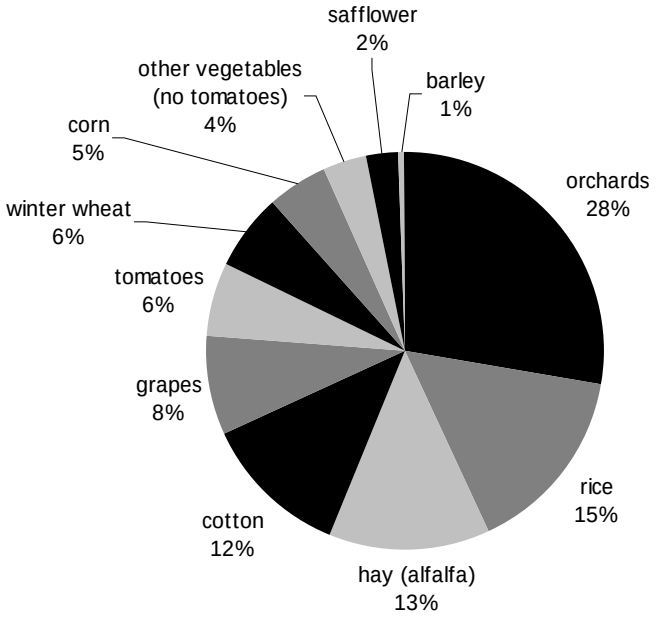

Figure 3.2. Relative surface area of the 11 most important commodities in the 10 California counties studied

Soil Data

Soil data was extracted from the Soil Survey Geographic Database (SSURGO) of the Natural Resources Conservation Service (NRCS). Estimates of soil physical parameters (e.g., texture, water holding capacity and potential rooting depth) were estimated from the geographic information system (GIS) version of the county soil survey maps, available within the SSURGO database. The SSURGO database is the digital form of the most detailed level of soil mapping done by the NRCS in the National Cooperative Soil Survey program.

Crop Types and Rotations

The crops modeled were limited to hay crops (which mainly consist of alfalfa), cotton, flooded rice, small grains (wheat, oats and barley), tomatoes, and corn/sorghum. To be consistent with typical crop rotations carried out in the Sacramento Valley, sunflower, and melons (honeydew, cantaloupe and watermelon) were also included. By limiting this study to these crops, the survey was focused while still accounting for about 50% of the land under crop production (1.5 million ha out of a total of about 2.9 million ha). Corn was simulated for grain in the counties of the Sacramento Valley and for silage in the San Joaquin Valley (USDA 2002).

To determine which crops were grown where, the California Department of Water Resources (DWR) land-use GIS survey was consulted. This product contains detailed maps of field locations and cultivated crops derived from analyses of aerial photos and field surveys. Solano and Placer Counties were surveyed in 1994; Yuba in 1995; Yolo in

1997; Colusa, Glenn, and Sutter in 1998; Butte in 1999; Fresno and Sacramento in 2000; and Kings in 2003.

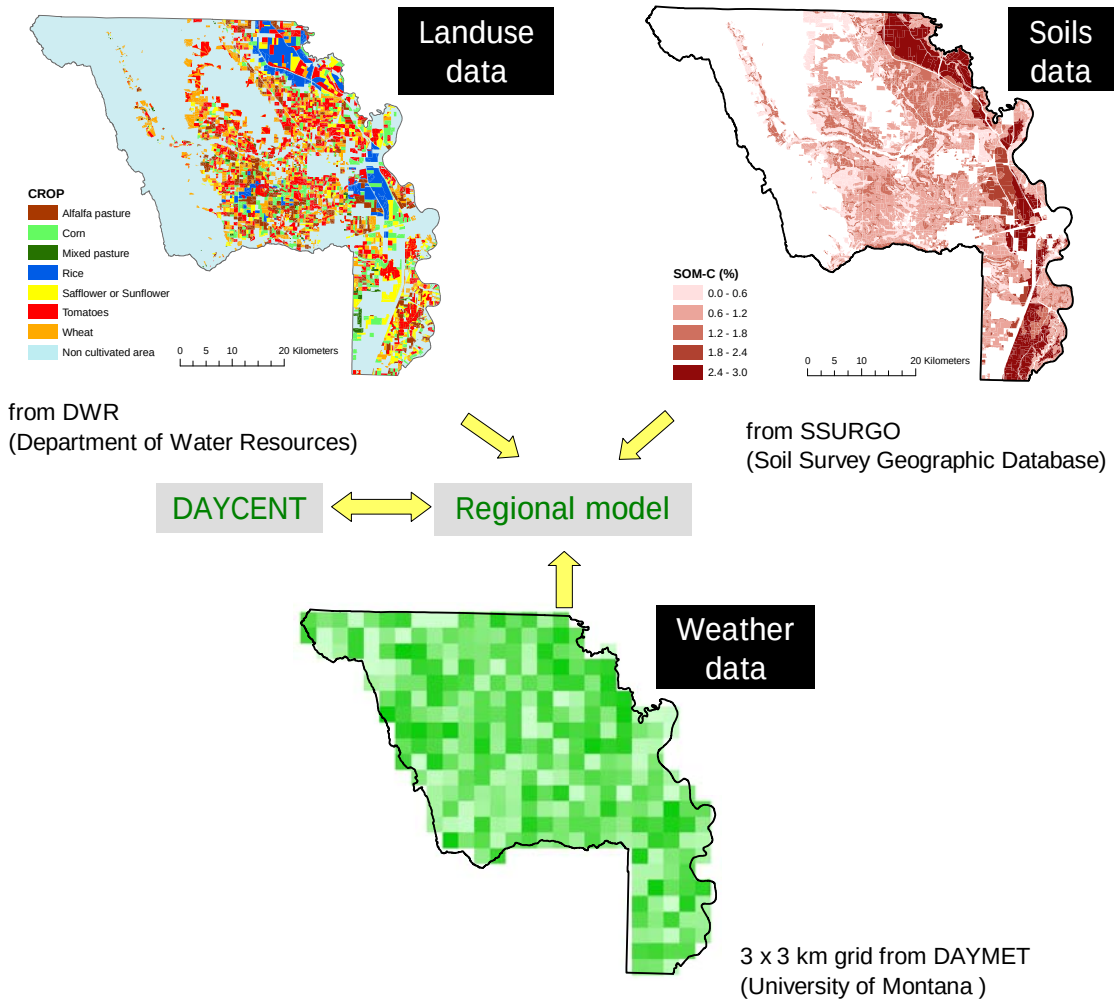

Figure 3.3. Data sources for the modeling strategy

Data on crop rotations are from pesticide use reports from agricultural commissioners and surveyed data. These were used to calculate the following conditional probabilities for each combination of crops:

$$\Pr(Cr_{t=2})|Cr_{t=1}, \text{ and} \qquad \text{[Equation 6]}$$

$$\Pr(Cr_{t=3})|Cr_{t=1}, Cr_{t=1}, \qquad \text{[Equation 7]}$$

where $\Pr(Cr_{t=2})$ is the probability to have crop Cr in the second year; $\Pr(Cr_{t=2})|Cr_{t=1}$ is then the probability of having a certain crop in the second year given that this farmer planted crop $Cr_{t=1}$ the year before, and so on. The data indicated that a farmer's decision

to plant a crop was only dependent on the crops that were planted two seasons before, or:

$$\Pr(Cr_{t=4})|Cr_{t=1}, Cr_{t=2,}Cr_{t=3} = \Pr(Cr_{t=4})|Cr_{t=2,}Cr_{t=3} \qquad \text{[Equation 8]}$$

An exception to this finding was alfalfa-hay, which was usually grown in a four- to five-year rotation. The conditional probabilities for alfalfa hay were adjusted accordingly. The crop modeled in the first year of the simulations (1997) was based on the DWR surveys. The crop following this crop (planted in 1998) was selected randomly according to the probabilities from Equation 6. In all subsequent years (until 2006), the crop planted was selected at random, according to the probabilities from Equation 7, except for rotations containing alfalfa-hay.

Management Practices

Details on conventional management practices in the region (e.g., planting, fertilization, irrigation, weed control, and harvesting) were obtained from the Agronomy Research and Information Center (AgRIC; http://agric.ucdavis.edu/) and the cost and return studies through the University of California Cooperative Extension (ARE 2007). The AgRIC is an outreach service that provides research-based, comprehensive, reliable information on current California agronomic cropping practices for alfalfa, corn, safflower, and small grains such as wheat. The cost and return studies contain details on agricultural inputs, planting, harvesting dates, and other operations for the six crops considered in this study. It is updated on a regular basis.

Next to conventional farming, all possible combinations of conservation tillage, manure application, and winter cover cropping were considered as possible alternative management options. For the winter cover-cropping option, a leguminous cover crop was assumed. Information on the management of these alternative cropping practices was obtained from farm advisors and the LTRAS at Russell Ranch of the University of California, Davis. All combinations of crops and management practices were considered, except for winter cover cropping for winter wheat and alfalfa, and reduced tillage and organic practices for alfalfa, as the latter is grown continuously for four growing seasons.

Climate Data

Spatially explicit climate data was extracted using the DAYMET model[4] developed at the Numerical Terradynamic Simulation Group of the University of Montana. This model uses a digital elevation model and daily observations from ground-based meteorological stations to produce a daily data set of temperature, precipitation, humidity, and radiation. It is available for the conterminous United States as 1 x 1 kilometer (km) grid cells for 1980 until 2003. However, due to computational constraints, the 1 x 1 km grid cells were combined into 3 x 3 km grid cells.

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[4] See www.daymet.org.

3.3.4. Modeling Approach

Historical Runs

To initialize the pool sizes, historical runs were performed on all modeling units. These historical runs were calibrated and validated in Section 2. Historical records of wheat yields in the state were used for calibration of historical biomass input.

Current Simulation and Calculations

Within each modeling unit, the net change in GWP with alternative management was calculated as follows:

$$\Delta GWP = -\frac{44}{12} \times \Delta SOC + 298 \times \Delta[N_2O] + 25 \times \Delta[CH_4], \qquad \text{[Equation 9]}$$

where ΔGWP is the global warming potential in Mg CO_2 equivalents (CO_2-eq) ha^{-1} yr^{-1}, ΔSOC is the simulated difference in soil organic C in Mg C ha^{-1} yr^{-1}, $\Delta[N_2O]$ is the simulated emission of N_2O in Mg N_2O ha^{-1} yr^{-1}, and $\Delta[CH_4]$ is the simulated emission of CH_4 in Mg CH_4 ha^{-1} yr^{-1}. The 44/12 ratio is used to convert mass of C to mass of CO_2, the 298 and 25 are the radiative forcing constants according to IPCC (2007a).

Statistical Analysis

Ten-year averages of emissions were analyzed with an ANOVA model in which crop, region (Sacramento Valley or San Joaquin Valley), tillage treatment, presence of cover cropping, and use of organic fertilizer and their interactions were considered as fixed effects.

3.4. Results

3.4.1. Historical Runs

At the end of the first period of the historical runs (grassland with extensive grazing), all SOM pools were in equilibrium (Figure 3.4). Subsequent dryland agriculture increased SOM content with about 10%, but the intensification of agriculture caused a 10% loss in the middle of the last century. From around 1970, C contents increased again. In this period, a minor decrease in slow C was offset by an increase in passive carbon.

Historical wheat yields are well recorded. Therefore, they are useful to validate the historical crop yields predicted by the model. There was a good correspondence in wheat yields between 1870 and 2000 (Figure 3.5). Nevertheless, the model predicted a slow decrease in yields between 1880 and 1950 due to nitrogen depletion, whereas the historical data show that yields increased in this period, mainly because farmers gradually adapted new technologies such as irrigation and mechanized soil tillage. The modeled change in farming practices was much more abrupt.

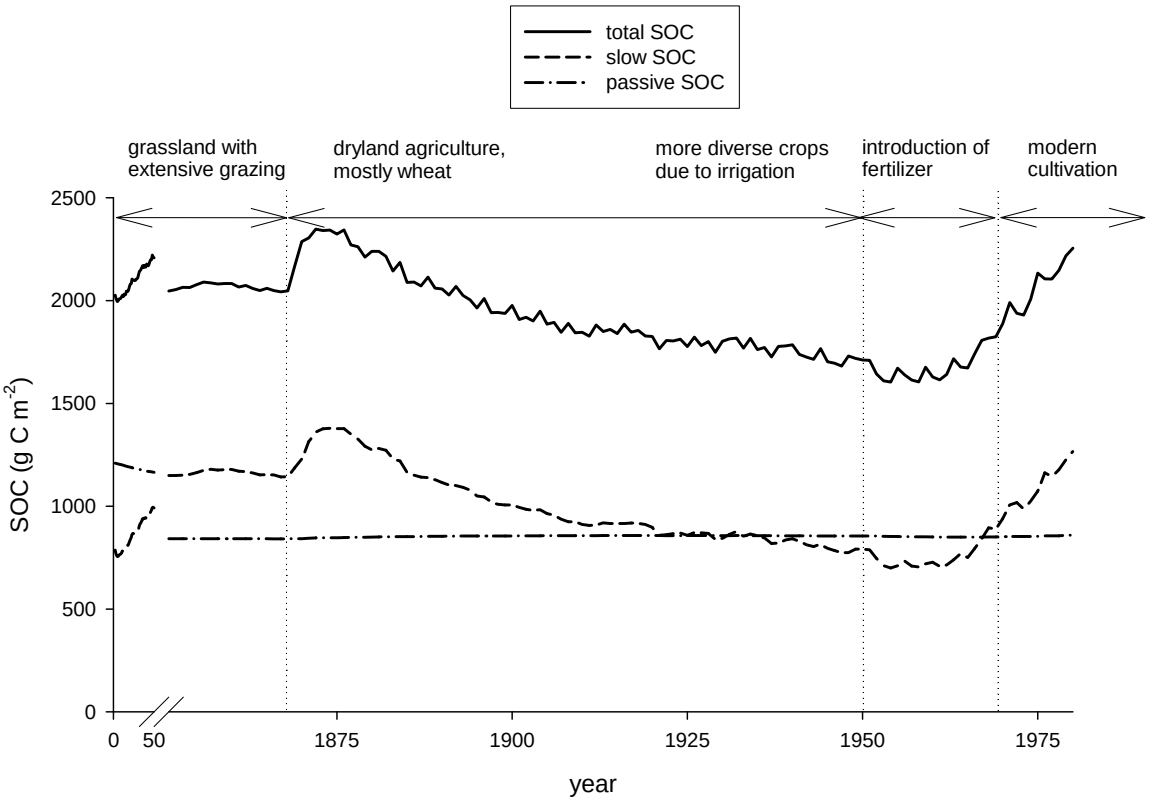

Figure 3.4. Typical modeled evolution of SOC in Yolo County between the years 0 and 1980 (example for Butte County)

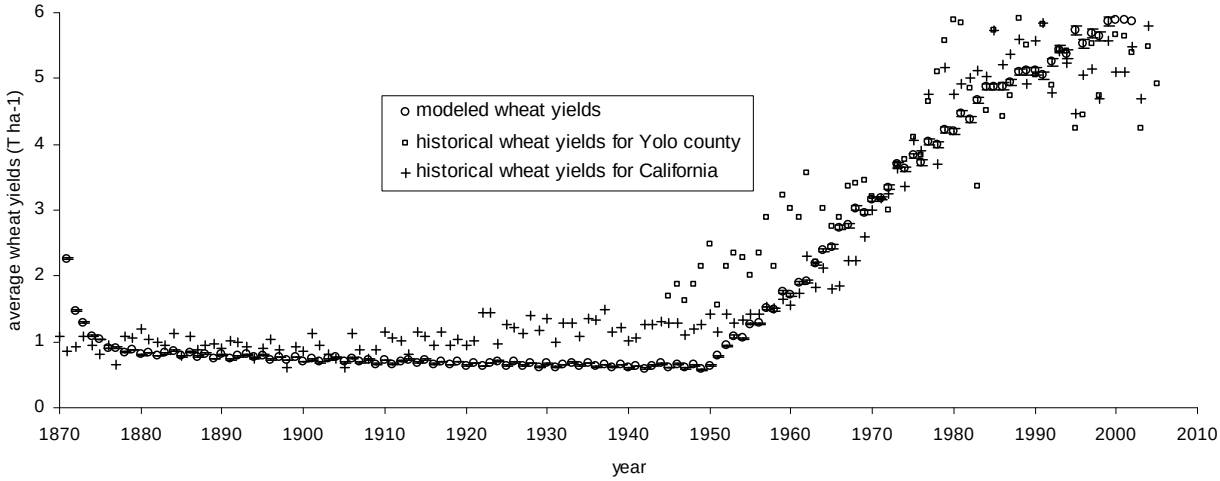

Figure 3.5. Modeled versus historical wheat yields

The model was able to satisfactorily predict county average yields under conventional management (Figure 3.6). However, within a crop, yearly differences among crop yields were less well modeled, indicating that the interannual variability due to weather conditions or crop pests was not as well simulated. For tomato, sunflower, and safflower, the modeled variability in county-wide averages was smaller than the variability in the averages reported by the USDA's National Agricultural Statistics Service (NASS). For alfalfa, corn, rice, and wheat, modeled variability and variability in reported yields were alike.

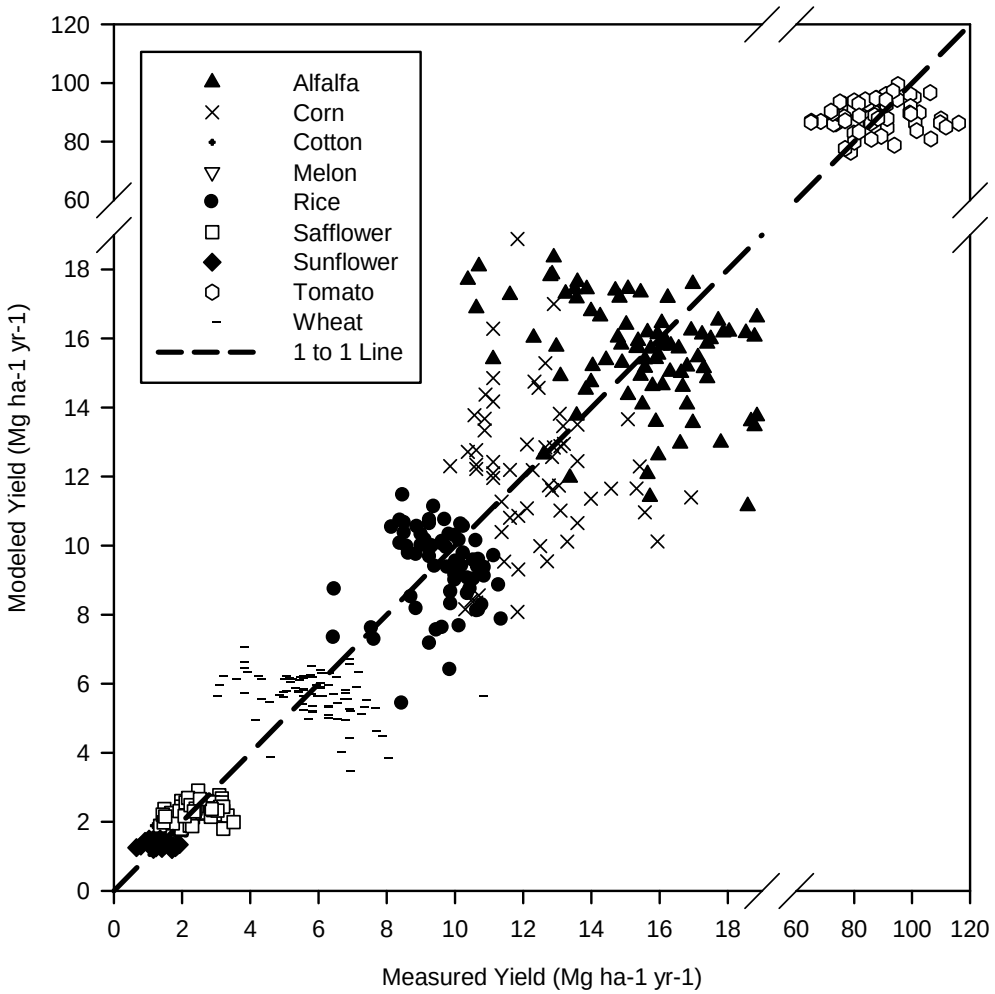

Figure 3.6. Measured versus modeled yields. Values are county-wide averages. Ten counties and ten years (1997–2006) were considered in this analysis.

3.4.2. Changes in Yields

In general, all alternative management practices decreased yields compared to conventional practices (Table 3.1 and Table 3.2). However, this effect was minimal: yields rarely decreased more than 5%. In the Sacramento Valley, the largest decrease was noted for the practice that combined both manure application and cover cropping (-2.4% averaged over all the crops). In the San Joaquin Valley, the largest decrease was noted for the practice that combined reduced tillage, manure application, and cover cropping (-3.5% averaged over all the crops). Reducing mineral fertilizer with about 25% decreased yields with about -2.9% and -2.3% averaged over all the crops in the Sacramento and San Joaquin Valley, respectively. All other management options had minimal (average < 1%) effects on yields. The yield declines were similar in the Sacramento Valley and the San Joaquin Valley.

Of all the crops considered, tomatoes showed the highest yield decrease (-2.5% and -3.1% in the Sacramento and San Joaquin Valley, respectively), followed by rice (-1.4% and -2%) and cotton (-2.9%) in the San Joaquin Valley. The other crops experienced smaller decreases in yield (around -1%).

Table 3.1. Average relative changes in yield (%) of alternative practices compared to conventional practices (conventional tillage, 100% mineral fertilizer, and no cover crop) for the Sacramento Valley. Values are averages over individual fields and for the period 1997–2006. Crops are grown in their typical rotations. Values are biophysical potentials not reflecting practical limitations of combining practices.

Tillage	Fertilizer	Cover crop	Alfalfa	Corn	Rice	Safflower	Sunflower	Tomato	Wheat
convent.	mineral, 75%	no	0.35	-0.20	-0.03	-12.9	-0.04	-4.00	-0.10
conserv.	mineral	no	0.01	3.10	0.14	0.07	0.16	-0.75	0.05
convent.	mineral	yes	0.30	-0.49	-0.44	4.48	-0.92	-1.31	0.10
conserv.	mineral	yes	0.30	-0.58	-0.43	4.34	-1.02	-1.33	0.12
convent.	manure	no	0.28	-1.88	-0.50	-3.64	-0.09	-1.72	-4.13
conserv.	manure	no	0.30	-2.99	-4.66	-0.60	-1.28	-4.39	-2.60
convent.	manure	yes	0.28	-2.45	-4.37	1.61	-0.97	-3.59	-2.37
conserv.	manure	yes	0.40	-3.28	-0.66	-6.27	0.02	-2.63	-1.94

Note: Convent. = conventional; conserv. = conservation

Table 3.2. Average relative changes in yield (%) of alternative practices compared to conventional practices (conventional tillage, 100% mineral fertilizer, and no cover crop) for the San Joaquin Valley. Values are averages over individual fields and for the period 1997–2006. Crops are grown in their typical rotations. Values are biophysical potentials not reflecting practical limitations of combining practices.

Tillage	Fertilizer	Cover crop	Alfalfa	Corn	Cotton	Melon	Rice	Tomato	Wheat
convent.	mineral, 75%	no	1.96	0.01	-2.10	-6.53	-0.05	-5.22	0.07
conserv.	mineral	no	0.39	1.56	-0.26	1.39	-0.20	-0.97	-0.19
convent.	mineral	yes	3.40	0.50	-3.58	-0.81	-2.52	-4.15	-0.14
conserv.	mineral	yes	3.47	0.59	-3.59	-0.81	-2.52	-4.15	-0.22
convent.	manure	no	0.01	0.08	-0.50	-1.06	-0.91	-0.27	-3.48
conserv.	manure	no	0.33	0.10	-1.09	1.05	-1.53	-0.84	-3.74
convent.	manure	yes	3.83	0.73	-5.23	-3.09	-3.98	-4.24	-3.41
conserv.	manure	yes	3.88	0.71	-6.45	-3.57	-4.40	-5.16	-3.93

3.4.3. Changes in GHG Emissions per Crop

This study's simulations indicated that the investigated alternative management practices led to the smallest decrease in GWP for alfalfa (Table 3.3 and Table 3.4). Averaged over all the alternative management practices, the highest emission reductions were achieved during seasons in which corn, rice, or tomato were grown (about -1.9 to -2.4 Mg CO_2-eq ha^{-1} yr^{-1}) in the Sacramento Valley and corn, cotton, or rice in the San Joaquin Valley (-1.6 to -3.9 Mg CO_2-eq ha^{-1} yr^{-1}).

Annual changes in GHG emissions due to alternative practices are to a large extent dependent on the crop grown during the growing season investigated. For example, in the Sacramento Valley, conservation tillage led to a small increase in GHG emissions for wheat (0.09 Mg CO_2-eq ha^{-1} yr^{-1}), and a small decrease for alfalfa (-0.01 Mg CO_2-eq ha^{-1} yr^{-1}). However, it decreased GHG emissions to a larger extent for rice (-0.83 Mg CO_2-eq ha^{-1} yr^{-1}) and tomatoes (-0.79 Mg CO_2-eq ha^{-1} yr^{-1}).

In addition, combining the different separate practices led to both negative and positive interactive effects. For example, conservation tillage did not lead to an additional reduction in GHG emissions when combined with winter cover cropping compared to the reduction observed by winter cover cropping alone (Table 3.5). In contrast, there was an additional effect of conservation tillage when combined with manure application. However, this additional effect depended strongly on the crop. More specifically, this additional effect was pronounced for rice and tomato, while it was much smaller for wheat (Table 3.3).

A rotation system including winter cover crops increased emissions in seasons when wheat was grown over the winter with about 0.16 Mg CO_2-eq ha^{-1} yr^{-1}). However, it led to a great decrease in GHG emissions when rice was grown (-2.25 Mg CO_2-eq ha^{-1} yr^{-1}). The additional effect of cover cropping when combined with other management options was again strongly dependent on the crop. There are additional decreases for rice and

tomato. Winter cover cropping even increased emissions when combined with manure application for safflower (Table 3.3).

Systems in which manure was applied increased GHG emissions slightly during seasons when alfalfa was grown (0.04 Mg CO_2-eq ha^{-1} yr^{-1}), and decreased emissions most notably for corn in the Sacramento Valley (-2.91 Mg CO_2-eq ha^{-1} yr^{-1}) and rice in the San Joaquin Valley (-2.38 Mg CO_2-eq ha^{-1} yr^{-1}). The additional effect of applying manure when combined with other options was very much dependent on the crop and location.

Table 3.3. Changes in the GWP, SOC, and nitrous oxide emissions for the Sacramento Valley. Averages were taken for each crop over 10 years (1997–2006), over all fields and crop rotations within multiple counties of the Sacramento Valley. Values are biophysical potentials not reflecting practical limitations of combining practices. Note that reductions in CO_2 emissions due to decreased fuel use in conservation tillage systems are not included in these values. These account for an extra reduction in GHG emissions of 0.25 to 0.50 Mg CO_2-eq ha^{-1} yr^{-1}.

Variable	Tillage	Fertilizer	Cover crop	Alfalfa	Corn	Rice	Safflower	Sunflower	Tomato	Wheat
GWP	convent.	mineral, 75%	no	-0.04	-0.70	-0.93	-0.02	-0.62	-0.79	-0.16
(Mg ha^{-1} yr^{-1})	conserv.	mineral	no	-0.01	-0.42	-0.83	-0.08	-1.44	-1.13	0.09
	convent.	mineral	yes	0.02	-0.93	-2.25	-0.44	-2.36	-1.79	0.19
	conserv.	mineral	yes	0.02	-0.95	-2.25	-0.48	-2.47	-1.80	0.16
	convent.	organic	no	0.03	-2.91	-1.26	-0.71	-0.54	-1.27	-0.75
	conserv.	organic	no	0.01	-3.17	-2.16	-1.46	-2.20	-2.70	-0.80
	convent.	organic	yes	0.08	-4.97	-3.54	-0.29	-1.44	-2.16	-0.66
	conserv.	organic	yes	0.06	-4.95	-4.46	-1.10	-3.03	-3.43	-0.59
DSOC	convent.	mineral, 75%	no	4.23	16.1	7.85	-105	19	-4.0	-6.9
(kg C ha^{-1} yr^{-1})	conserv.	mineral	no	2.72	56	123	56.8	316	213	-28
	convent.	mineral	yes	-4.01	193	580	144	557	410	-49
	conserv.	mineral	yes	-4.17	196	579	157	585	413	-41
	convent.	organic	no	-10.13	600	227	108	144	227	86
	conserv.	organic	no	-5.59	623	372	267	491	514	108
	convent.	organic	yes	-21.03	1171	665	53.7	361	411	79
	conserv.	organic	yes	-17.17	1132	832	230	705	675	50
N2O flux	convent.	mineral, 75%	no	-0.06	-1.37	-1.92	-0.88	-1.18	-1.71	-0.40
(kg N ha^{-1} yr^{-1})	conserv.	mineral	no	0.00	-0.46	-0.80	0.27	-0.60	-0.74	-0.02
	convent.	mineral	yes	0.01	-0.48	-0.27	0.20	-0.67	-0.61	0.02
	conserv.	mineral	yes	0.01	-0.49	-0.27	0.21	-0.69	-0.61	0.02
	convent.	organic	no	-0.02	-1.51	-0.90	-0.68	-0.03	-0.94	-0.92
	conserv.	organic	no	-0.03	-1.89	-1.71	-1.02	-0.84	-1.74	-0.86
	convent.	organic	yes	0.00	-1.44	-2.35	-0.19	-0.26	-1.40	-0.79
	conserv.	organic	yes	0.00	-1.70	-3.01	-0.54	-0.96	-2.04	-0.86

Note: Convent. = conventional; conserv. = conservation

Table 3.4. Changes in the global warming potential (GWP), soil organic carbon (SOC), and nitrous oxide emissions for the San Joaquin Valley. Averages are taken for each crop over 10 years (1997–2006), over all fields and crop rotations within multiple counties of the San Joaquin Valley. Note that reductions in CO_2 emissions due to decreased fuel use in conservation tillage systems are not included in these values. These account for an extra reduction in GHG emissions of 0.25 to 0.50 Mg CO_2-eq ha^{-1} yr^{-1}.

Variable	Tillage	Fertilizer	Cover crop	Alfalfa	Corn	Cotton	Melon	Rice	Tomato	Wheat
GWP	convent.	mineral, 75%	no	-0.23	-0.63	-0.64	-0.32	-2.34	-0.61	-0.13
(Mg ha^{-1} yr^{-1})	conserv.	mineral	no	-0.04	-0.92	-0.65	-0.29	-1.10	-0.60	-0.14
	convent.	mineral	yes	0.05	-0.98	-2.08	-0.25	-3.79	-1.24	-0.08
	conserv.	mineral	yes	0.05	-1.02	-2.10	-0.25	-3.79	-1.24	-0.11
	convent.	organic	no	0.04	-1.42	-0.55	-0.90	-2.38	-0.20	-0.91
	conserv.	organic	no	-0.02	-2.38	-1.26	-1.12	-3.56	-0.94	-1.36
	convent.	organic	yes	0.26	-3.42	-2.36	-1.17	-6.38	-1.37	-0.87
	conserv.	organic	yes	0.20	-4.00	-3.10	-1.41	-7.55	-2.24	-1.02
DSOC	convent.	mineral, 75%	no	5.21	2.43	-0.17	-18.9	6.13	-8.2	0.65
(kg C ha^{-1} y^{r-1})	conserv.	mineral	no	7.64	176	108.1	44.8	136	89.6	29.2
	convent.	mineral	yes	-7.5	264	428	95.1	678	330	13.8
	conserv.	mineral	yes	-7.1	276	433	95.1	678	329	22.0
	convent.	organic	no	-18.8	344	151	240	158	154	112
	conserv.	organic	no	-5.0	548	267	269	313	286	219
	convent.	organic	Yes	-45.9	884	462	302	719	392	105
	conserv.	organic	yes	-33.7	1017	609	346	914	538	132
N_2O flux	convent.	mineral, 75%	no	-0.45	-1.33	-1.38	-0.83	-4.96	-1.38	-0.27
(kg N ha^{-1} yr^{-1})	conserv.	mineral	no	-0.03	-0.58	-0.54	-0.27	-1.28	-0.59	-0.06
	convent.	mineral	yes	0.05	-0.02	-1.07	0.20	-2.79	-0.07	-0.06
	conserv.	mineral	yes	0.06	-0.01	-1.07	0.20	-2.79	-0.07	-0.06
	convent.	organic	no	-0.05	-0.34	0.02	-0.04	-3.85	0.78	-1.06
	conserv.	organic	no	-0.09	-0.78	-0.60	-0.28	-5.14	0.23	-1.19
	convent.	organic	yes	0.19	-0.38	-1.41	-0.12	-7.99	0.14	-1.03
	conserv.	organic	yes	0.16	-0.59	-1.84	-0.31	-8.96	-0.57	-1.14

Note: Convent. = conventional; conserv. = conservation

3.4.4. Average Changes in GHG Emissions

Over a time period of 10 years, decreases in GHG emissions averaged per alternative management practice but across the different crops occurring within typical crop rotations ranged from -0.7 to -3.23Mg CO_2-eq ha^{-1} yr^{-1} in the Sacramento Valley, and from -0.5 to -2.5 in the San Joaquin Valley (Table 3.5). In general, reducing fertilizer and conservation tillage had the least potential to reduce GHG emissions. Reducing fertilizer led to decreased emissions of -0.89 and -0.61 Mg CO_2-eq ha^{-1} yr^{-1} (respectively in the Sacramento and San Joaquin Valleys), while conservation tillage decreased emissions with -0.68 and -0.57 Mg CO_2-eq ha^{-1} yr^{-1}.

Table 3.5. Weighed averages of changes in the GWP, SOC, and nitrous oxide emissions. Averages are taken for each crop over 10 years (1997–2006) over all fields and crop rotations within multiple counties of the Sacramento Valley versus the San Joaquin Valley. Standard deviations represent the uncertainty around GHG emissions for one single field if this field was under the specific management for 10 years. Note that reductions in CO_2 emissions due to decreased fuel use in conservation tillage systems are not included in these values. These account for an extra reduction in GHG emissions of 0.25 to 0.50 Mg CO_2-eq ha^{-1} yr^{-1}.

Tillage	Fertilizer	Cover crop	GWP (Mg CO_2-eq ha^{-1} yr^{-1})		ΔSOC (kg C ha^{-1} yr^{-1})		N_2O (kg N ha^{-1} yr^{-1})	
			Sacramento Valley					
convent.	mineral, 75%	no	-0.89	± 0.76	-2	± 16	-1.92	± 1.59
conserv.	mineral	no	-0.68	± 0.36	103	± 34	-0.64	± 0.56
convent.	mineral	yes	-1.36	± 0.89	310	± 180	-0.48	± 0.94
conserv.	mineral	yes	-1.37	± 0.88	312	± 178	-0.48	± 0.94
convent.	Organic	no	-1.16	± 0.78	158	± 63	-1.23	± 1.51
conserv.	Organic	no	-1.94	± 1.03	288	± 88	-1.89	± 1.86
convent.	Organic	yes	-2.60	± 1.87	405	± 212	-2.38	± 2.81
conserv.	Organic	yes	-3.29	± 2.07	532	± 246	-2.86	± 2.98
			San Joaquin Valley					
convent.	mineral, 75%	no	-0.61	± 0.58	-4	± 14	-1.33	± 1.24
conserv.	mineral	no	-0.57	± 0.33	81	± 35	-0.59	± 0.55
convent.	mineral	yes	-1.35	± 1.07	284	± 170	-0.66	± 1.36
conserv.	mineral	yes	-1.38	± 1.08	287	± 169	-0.68	± 1.39
convent.	Organic	no	-0.49	± 0.89	154	± 54	0.16	± 1.96
conserv.	Organic	no	-1.14	± 0.90	255	± 79	-0.43	± 1.82
convent.	Organic	yes	-1.87	± 1.41	395	± 203	-0.89	± 2.41
conserv.	Organic	yes	-2.45	± 1.52	498	± 235	-1.32	± 2.41

Convent. = conventional; conserv. = conservation

Manure application led to a greater reduction in the Sacramento Valley (-1.16 Mg CO_2-eq ha^{-1} yr^{-1}) compared to the San Joaquin Valley (-0.5 Mg CO_2-eq ha^{-1} yr^{-1}), winter cover cropping decreased GHG emissions with -1.36 and -1.35 Mg CO_2-eq ha^{-1} yr^{-1}. Combining these single management options led to even greater reductions in GHG emissions. Most notably, combining cover cropping with manure application showed great potential (-2.60 and -1.87 Mg CO_2-eq ha^{-1} yr^{-1}). The greatest potentials were reached by combining conservation tillage, manure application, and winter cover cropping (-3.29 and -2.45 Mg CO_2-eq ha^{-1} yr^{-1}). Potentials in the San Joaquin Valley were, on average, 25% smaller than the potentials in the Sacramento Valley (except for cover cropping with mineral fertilization). Furthermore, increases in SOC are responsible for about 70%–80% of the reductions in GHG emissions for the different treatments.

3.5. Discussion

3.5.1. Simulated Changes in Yield Under Alternative Management

General yield trends in conventionally managed systems were simulated adequately (Figure 3.6). The effects on yields of alternative practices were minimal (Table 3.1 and 3.2). The greatest reductions in yields were simulated for tomatoes and safflower (up to 13%). However, reductions in yields were generally less than 4%. This observation corresponds with what has been reported in the literature. For example, Miguez and Bollero (2005) found that when organic fertilizer was applied in winter cover cropping systems, there was no difference in corn yields. Similarly, organic farming did not lead to consistent declines or increases in wheat yields in a study in a Mediterranean climate (Deria et al. 2003). The same was found for tomatoes in California (Drinkwater et al. 1995). Cover cropping frequently even increases yields: in a review, Snapp et al. (2005) reports yield increases up to 15%. Increases in yield were observed for safflower in the Sacramento Valley and corn in the San Joaquin Valley.

The lack of response of simulated yields to the alternative practices is over-optimistic, because the DAYCENT does not take all limitations of crop growth into account. For example, the model ignores a possible higher aptitude for diseases and pests under certain cropping practices (Karungi et al. 2006). It also does not simulate the decreased seedling growth when a crop is sown within crop stubble, as is the case for conservation tillage. In addition, only carbon and nitrogen fluxes were simulated; deficiencies in other macronutrients (phosphorus, sulfur) or micronutrients (e.g., zinc, molybdenum) were disregarded. The reported decreases in yield therefore only represent possible N and moisture limitations.

It may seem surprising that applying 25% less fertilizer decreased yields in some crops up to only 8%. This indicates that the conventional amount of fertilizer applied in this area is above what is actually needed for crop growth. Overfertilization is a common practice due to the low price of nitrogen fertilizer and the minimization of the risk of yield reduction due to nitrogen limitation (Cassman et al. 2002).

3.5.2. Comparison of Changes in Soil Carbon and Trace Gas Fluxes With Literature Data

The range in the presented average simulated differences in SOC corresponds with what is reported in the literature. In the conservation tillage system, an average increase in soil C of about 100 kg C ha^{-1} yr^{-1} or 0.3 Mg CO_2-eq ha^{-1} yr^{-1} was found. This is somewhat smaller than average values reported in the literature for no-tillage systems. Franzluebbers (2005) reported a value of 1 Mg CO_2-eq ha^{-1} yr^{-1}, and Six et al. (2004) a value of 0.8 Mg CO_2-eq ha^{-1} yr^{-1}, for a 10-year-old no-tillage system in a humid climate. The reduction in intensity of the conservation tillage system simulated (validated using long-term field experiments, see Section 2), is quite minimal compared to the no-tillage systems referred to in the above-mentioned studies. The simulated increase in SOC for the conservation tillage and winter cover cropping system (1.1 Mg CO_2-eq ha^{-1} yr^{-1}) is larger than the average SOC increase for no-tillage winter cover cropping systems reported by Franzluebbers (2005) (0.6 Mg CO_2-eq ha^{-1} yr^{-1}). In addition, assuming that manure was applied at an average rate of 1 Mg C ha^{-1} yr^{-1}, a manure C to SOC conversion rate of 13% was simulated. This value is very close to the conversion rate of 17% based on field measurements from Franzluebbers (2005). For no-tillage systems, Six et al. (2004) reported changes in N_2O emissions between -1.2 and 0.2 Mg CO_2-eq ha^{-1} yr^{-1}, depending on the duration of the experiment. This study's simulated average is in the middle of this range (-0.41 ± 0.23 and -0.38 ± 0.35 kg N ha^{-1} yr^{-1} for the Sacramento and San Joaquin Valleys, respectively).

3.5.3. Evaluation of the Reduction Potentials

The DAYCENT model simulated potential reductions in GHG emissions on the order of -0.7 to -3.3 Mg CO_2-eq ha^{-1} yr^{-1} for the Sacramento Valley and -0.5 to -2.5 Mg CO_2-eq ha^{-1} yr^{-1} for the San Joaquin Valley (Table 3.5). These values are averages over different crops as they are cultivated in their typical rotations. Although the potential for individual crops might be greater than these averages (e.g., rice in the Sacramento Valley has a potential reduction of up to -4.7 Mg CO_2-eq ha^{-1} yr^{-1}), a typical crop rotation will include a variety of crops which can have a smaller GHG mitigation potential. Although the emission reductions of single management options are modest, our results indicate that combining these options may lead to larger reductions. Most markedly, combining manure application with winter cover cropping seems to be an efficient option to reduce GHG emissions. The treatment in which all three carbon-sequestering options are combined (conservation tillage with manure application and winter cover cropping) might have the largest potential reduction, but it does not seem feasible from a farmer's operational standpoint.

The DAYCENT model cannot simulate flooded conditions. Therefore, the presented values for rice systems are only provisional and should only be used as very rough indicators. The main assumption behind the presented numbers is that methanogenesis was not affected by the management options considered. For example, the assumption behind the reported reduction in GHG emissions due to reduced tillage in rice systems for the Sacramento Valley (-0.83 Mg CO_2-eq ha^{-1} yr^{-1}) is that the amount of methane

produced under conventional practices is equal to the amount of methane produced under conservation tillage.

The reported decreases in GHG emissions were for a large part due to gains in SOC (e.g., 90% for winter cover cropping, 70%–80% for manure application). In general, management options that introduced the most carbon to the soil led to the largest reduction in GHGs. This was the case for the systems combining manure application and winter cover cropping. However, the capacity of a soil to store C is limited (VandenBygaart et al. 2002; Six et al. 2004), and if the proper soil management is not maintained, all sequestered C will be released again to the atmosphere. Management options that rely almost solely on increases in soil C (e.g., winter cover cropping) seem only a viable option to curb GHG mitigation in the short term (i.e., 10–20 years, when C equilibrium is reached). A (quite consistent) decrease in N_2O emissions of about 0.5 Mg CO_2-eq ha^{-1} yr^{-1} was simulated when applying manure instead of mineral fertilizer (however, this is not the case in the San Joaquin Valley). The organic farmed soils contained less mineral N than conventionally fertilized soils, leading to less N_2O emissions. Because the use of manure instead of mineral nitrogen reduces N_2O emissions, it is a more permanent option to reduce GHG emissions and a better solution in the long term.

The 25% fertilizer reduction system had a modest overall potential to decrease GHG (-0.9 Mg CO_2-eq ha^{-1} yr^{-1} in the Sacramento Valley and -0.6 Mg CO_2-eq ha^{-1} yr^{-1} in the San Joaquin Valley). Nonetheless, nearly all of this decrease is due to a decrease in N_2O emissions, which does not have the issue of permanence (VandenBygaart et al. 2004). Decreasing N_2O emissions in low-input systems indicate that conventional systems are overfertilized and that the surplus of mineral N that is not taken up by the crop is high. This surplus might be denitrified when there is a supply of C-substrate and sufficient moisture (McSwiney and Robertson 2005). In addition, the costs to implement this strategy will be similar or even less than the conventional system. Therefore, low input systems seem to be an efficient way to permanently mitigate GHG emissions, regardless of the duration of the practice. A similar argument can be made for conservation tillage systems. A reduction of tillage operations is rather simple to implement, and it leads to a direct reduction in costs and a reduction in fuel-related GHG emissions, which are permanent. The fuel-related reductions are, however, not included in the current calculations. They would account for an extra reduction in GHG emissions of 0.25 to 0.50 Mg CO_2-eq ha^{-1} yr^{-1}.

In general, cropping systems in the Sacramento Valley showed more potential to mitigate GHGs than cropping systems in the San Joaquin Valley. It is hypothesized that the higher temperatures in the San Joaquin Valley increase the decomposition of SOC compared to the Sacramento Valley. Since increases in SOC are most important for GHG mitigation, these greater SOC decomposition rates in the San Joaquin Valley decrease the GHG mitigation potentials significantly.

3.5.4. Model Uncertainties

The standard deviations of the averaged potential GHG reductions are large, and often in the order of magnitude as the average itself. However, these standard deviations are representative for single fields. They represent the range in GHG emission reduction that one can expect when a random field would be chosen in the Sacramento or San Joaquin Valley to be put under a certain alternative management for 10 years. This variability originates mainly from soil characteristics. Therefore, if different fields are aggregated the uncertainty around the average estimate of the reductions across all fields will be less. Since the success of a carbon trading system is dependent on the quality of estimates of greenhouse gas emissions, aggregated carbon credit contracts will be necessary to reduce the uncertainty around potential sequestration rates.

In the case of N_2O emissions, the standard deviations are even larger, and often three times the average value. This is a well-known phenomenon. For example, Winiwarter and Rypdal (2001) concluded that the uncertainty around N_2O emissions of agriculture is the main source of uncertainty in the national inventory of all greenhouse gases from all sources. This variability is incurred by the dependence of nitrification and denitrification on moisture levels in the soil, and these levels are highly variable. In addition, the amount of mineral N available in the soil for nitirification and denitrification is highly dependent on crop N demand. Winiwarter and Rypdal (2001) estimated that the uncertainty (quantified as 2σ) around agricultural N_2O emissions is about 120%, while this is only 36% for CH_4 and 3% for CO_2. A concerted research effort will be necessary to further our understanding of these mechanisms. This will lead to more accurate biogeochemical models and better quality prediction of N_2O flux reductions.

3.5.5. Conclusions

It was simulated that yields were affected only very minimally (< 8%) by the alternative management practices considered. The reduction in GHG emissions of individual practices (conservation tillage, manure application, or winter cover cropping) were modest (< 1 Mg CO_2-eq ha^{-1} yr^{-1}). However, combining individual practices led to larger reductions. In the Sacramento Valley, the GHG mitigation potential ranged from -0.7 to -3.3 Mg CO_2-eq ha^{-1} yr^{-1}. The GHG mitigation potential was smaller for the San Joaquin Valley (from -0.5 to -2.5 Mg CO_2-eq ha^{-1} yr^{-1}). This difference was attributed to the higher temperature in the San Joaquin Valley. In general, most of this reduction in emissions was achieved by increases in soil C through increases in the level of C input. Because the capacity of a soil to store C is limited, these options are non-permanent. Although the 25% fertilizer reduction system had a modest overall potential to decrease GHG, nearly all of this decrease is due to a decrease in N_2O emissions. Therefore, this practice does not have the issue of permanence. Similarly, the reduction of fuel use, and consequently CO_2 emissions from fuel burning, are a permanent reduction in GHG emissions associated with conservation tillage practices. The standard deviations of the potential GHG reductions are substantial. Only a concerted research effort can advance the

general understanding of the processes involved and decrease the uncertainty around these estimates.

4.0 Economic Potential of Carbon Sequestration at the County Level: Yolo County, California

The complexity of identifying the most effective and economically efficient techniques for carbon sequestration in agriculture demands as a first step a disaggregated analysis by region. This study focused on Yolo County, an important agricultural county in Northern California.[5] It is also a county with a large diversity of crops and soils.

According to the last Land Use Survey of the Department of Water Resources for Yolo County, conducted in 1997, 48 different crops are cultivated in the county. As discussed in the first part of this report, wheat, tomato, and corn are the main crops in the county, followed by alfalfa, rice and safflower. Since each crop has a differentiated potential to store carbon, a crop-specific investigation must be undertaken to analyze the effectiveness of mitigation based on carbon sequestration. Nitrogen-based inputs traditionally used intensively in agriculture are proportional to changes in the decay rate of SOM in the soil. That is the reason why carbon sequestration has to be carefully analyzed from an integrated perspective, where the soil dynamics and the economics of each crop production have to be studied with a high degree of specificity.

Agriculture can help to mitigate GHGs in two ways: (1) decreasing the emissions caused by agriculture, and (2) sequestration of CO_2 in biomass and soils. Effective mitigation policies based on agriculture must therefore consider both methods. Decreasing GHG emissions occurs through more efficient use of traditional inputs in intensive agriculture, such as fuel, fertilizer nitrogen, and pesticides. Carbon sequestration also occurs through improved management of established agricultural land for the purpose of effectively improving or restoring SOM. By altering the decay rate of SOM in the soil, the carbon equilibrium becomes altered for many periods after a change in the input-mix and management. The common features of reduced-till, cover cropping, and organic systems are that soil erosion and disturbance are minimized, while the efficiency of water and nutrients are maximized. These practices also typically aim to generate as much crop residue as possible.

To what extent have these alternative practices been implemented so far in Yolo County? The information on acreage managed under reduced-till is imprecise and scarce. There is practically no information on how many acres are under cover-cropping practices. The National Crop Residue Management Survey (CTIC 2002) offers information on acreage and crops under reduced-till and conservation tillage, but the results may not be significant at the county level. Acreage for organic systems is also difficult to assess, and only through personal communications with extension specialists could it be obtained. Therefore, one can say that there is no reliable information at the aggregate level on adoption of conservation practices in Yolo County, or in California in general.

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[5] Agriculture is Yolo County's primary industry.

To study the biophysical and economic potential of different alternatives in Yolo, researchers used both an agronomic process model, DAYCENT (already presented in Section 2 of this report) and an economic/behavioral model that captures heterogeneity in observable and unobservable factors that influence farmers' decisions on what crop and management systems to adopt in a given field. DAYCENT enabled the simulation of GHG fluxes, SOC, and nitrogen stocks over agricultural fields in Yolo County. Its crop growth sub-model simulates crop growth, dry matter production, and yields to estimate the amount and quality of residue (i.e., carbon input) returned to the soil under different management practices and field-level soil characteristics.

To tailor DAYCENT to Yolo County, each unique combination of soils, crop type, and microclimate in the county was modeled. To do this, an overlay was created of the GIS formed by soil information from the USDA's SSURGO database, the crop information from DWR's Land Use Survey, and climate data from DAYMET. This was done using the software ArcGIS version 9. As mentioned, the result of this overlay was a database containing 11,611 unique combinations of soils, crops, and climates. The framework specifically developed to create all input files necessary to run the DAYCENT model for each of these units enables us to carry out a large number of simulations over different gradients of soils, climates, crops, and management strategies (and interactions of these variables).

Three steps were successively completed, to assess the economic potential of a carbon sequestration policy in Yolo County:

- The use of DAYCENT was screened in the economic analysis of carbon sequestration payments using information on experimental sites.
- Once the experimental data was used, a survey was applied to identify the information needed to conduct an economic analysis incorporating behavioral aspects.
- Once the survey data was obtained, it was combined with DAYCENT, and the resulting data was loaded on an econometric model to determine how farmers would react to carbon sequestration payments.

5.0 Screening the Potential of DAYCENT for Economic Analysis: An Application to Experimental Sites

The University of California at Davis, in an effort to study the long-term sustainability of conventional and alternative agriculture cropping practices, created the LTRAS project. LTRAS was initiated in 1993 on 69 acres in Yolo County, California, as a way of obtaining precise information on management and soil properties at the plot level. DAYCENT is used to simulate the carbon and nitrogen fluxes precisely for each land use/management treatment. The present study analyzed two corn-tomato rotations under conventional management and under organic management. Each management treatment was analyzed in conventional tillage, cover crops, and manure applications (CT+CC+MA) for almost nine years. Details of the experiment can be found in Denison et al. (2004).

In addition to the data from the LTRAS project, the present study employs data from another large scale field experiment, the SAFS project, conducted by the Agronomy Farm of the University of California at Davis. The SAFS project encompassed four rotations between years 1989–2000 in a 20-acre field (Clark et al. 1998). The rotations were tomato-safflower-corn-wheat-bean under conventional management (CT) and cover-cropping (CT+CC). A more in-depth description of the experiment can be found in Mitchel et al. (2005).

Finally, data from the Five Points experimental site in Fresno, California, is used in this study to obtain a better understanding of conservation tillage. Five Points encompasses 7.9 acres devoted to treatments of a tomato-cotton rotation: conventional tillage with and without cover crops (CT, CT+CC) and conservation tillage with and without cover crops (RT, RT+CC).

Detailed records on variable and fixed costs were recovered from all experimental sites using standard engineering equations to estimate variables such as labor hours, fuel-use, and others.[6] Actual input data and yields were also recorded. Analyses were computed in two ways—including and excluding fixed costs (including cash costs and non-cash costs). Input prices were scaled for other years using the evolution of prices paid by the farmers at the national level summarized by the National Agricultural Statistics Service. Crop prices for each simulated year for Yolo and Fresno counties are from the County Agricultural Commissioners Data for all years except 2004, for which data were taken from the Environmental Protection and Agricultural Services of Yolo County.

Greenhouse gas mitigation costs were then computed using the change in profitability of the transition from a conventional practice to an alternative practice. *Profitability* was

[6] For LTRAS, operations were recorded only for 2003. However, management practices changed little over the course of the experiment, and this was not considered a major source of uncertainty.

defined in this context as net present value (*NPV*) of the respective agricultural system. The GHG mitigation cost was discounted based on a common time horizon of *t* to *T*, as well as on the rate at which farmers discount their future potential profits (r), and then it was computed as an annualized fixed payment (*P*) such that:

$$P = \frac{NPV_{Conv} - NPV_{\overline{Conv}}}{\sum_{t=1}^{T}(1+r)^{-t}} \quad . \qquad \text{[Equation 10]}$$

NPV denotes the net present value of agricultural production under the specific management practice (*m*) summed over all years *T* of the rotation such that:

$$NPV_t = \sum_{t=1}^{T} \frac{R_{mt} - TVC_{mt}}{(1+r)^t} \quad , \qquad \text{[Equation 11]}$$

where *R* denotes revenue and *TVC* are total variable costs. Once the payment (*P*) is computed using site-specific budget data, an annualized mitigation price (*p*) of changing management from conventional practice to an alternative practice can be computed as:

$$p = \frac{P}{\frac{\sum_{t=1}^{T} \Delta GWP_t}{T}} \quad , \qquad \text{[Equation 12]}$$

where the denominator represents the mean mitigation in GWP averaged over the entire rotation.[7] All economic magnitudes are calculated in U.S. dollars per year and hectare, while GWP is calculated in Mg CO_2-eq yr^{-1} ha^{-1}. Great variability was found in yield (and hence in revenue) between conventional and alternative practices in all experiments, which contaminated the computed *p*. This variability can be conceptualized as follows. Actual yields are just realizations of a random variable whose distribution is governed by environmental conditions such as weather or pest occurrence, which were not controlled for in these computations. Also, there is an extra variability caused by the acquisition of the know-how to apply innovative management at the experimental sites. On the other hand, the goals of the managers do not reflect other balancing forces, such as economic pressures faced by actual farmers, with skills on how to manage agronomic and economic constraints. All these factors contribute to the large variability in yields from the experimental sites.

Results of this analysis of the experimental field stations are presented in Table 5.1 and Table 5.2. The site- and treatment-specific average GHG mitigation costs per hectare per year ranged broadly, from more than $300 per metric ton at SAFS to zero in the profitable reduced-tillage treatment at Five Points. The alternative cropping practices demonstrate mitigation costs per unit that are more congruent with those cited in the literature than the conventional practices. This result is due to the fact that the

[7] This average is controversial, but since weather conditions were assumed constant to compute GWP, it was considered reasonable for this crude analysis.

alternative systems were not substantially less profitable than the alternative systems at LTRAS and SAFS, and furthermore had substantial levels of GHG mitigation. However, the organic systems at LTRAS showed a large GHG mitigation, largely due to high soil carbon sequestration. However the management practices at LTRAS resulted in much lower profitability when compared to the alternative systems at Five Points.

In terms of input costs in the three experiments, the choice of management was not sensitive to inclusion or exclusion of fixed costs. Since these costs were fairly similar between alternative and conventional systems, excluding the fixed costs raised the mitigation prices by $1 to $5 per Mg CO_2 equivalent. To explore the sensitivity of the price of mitigation to potential improvements in yield consistency of alternative management, this study's researchers identified typical scenarios for each experiment, using quartiles of the empirical distribution of yields at each site. The sensitivity study shows that mitigation price varies greatly across the groups: the price at LTRAS expected cost lowers to $49.46 and to $17.41 at SAFS per Mg CO_2-eq.

Table 5.1. Rotational Effects on Revenue, Total Variable Cost, and Profit

	LTRAS			SAFS				
	$ct \rightarrow ct + cc + ma$			$ct \rightarrow ct + cc$				
	Corn	**Tomato**	**NPV**	**Beans**	**Corn**	**Safflower**	**Tomato**	**NPV**
ΔR	-385	345	-49.07	260	75	-171	-164	20.64
ΔTVC	99	295	584.89	30	-97	90	670	615.03
$\Delta \pi$	-483	-170	-629.68	230	141	-255	-879	-658.72
			Rotation					Rotation
ΔGWP	-2.62	-3.59	-6.21	1.47	-0.76	-1.99	-1.14	-2.42
$p\left(\$/MgCO_2e\right)$	105.98			292.91				

Economic magnitudes in $\$ha^{-1}yr^{-1}$ and GWP in $MgCO_2eha^{-1}yr^{-1}$. Δ indicates the difference between conservation and conventional outcomes; π stands for (net) profits.

Table 5.2. Rotational Effects at Five Points on Revenue, Total Variable Cost, and Profit

	$ct \rightarrow ct + cc$			$ct \rightarrow rt$			$ct \rightarrow rt + cc$		
	Cotton	**Tomato**	**NPV**	**Cotton**	**Tomato**	**NPV**	**Cotton**	**Tomato**	**NPV**
ΔR	475	280	-126.77	476	280	144.53	-366	-21	-207.07
ΔTVC	20	-22	149.11	-60	-74	-91.52	-28	-100	-84.96
$\Delta \pi$	-24	-141	-184.89	-7	326	298.78	-153	-283	-364.31
			Rotation			Rotation			Rotation
ΔGWP	-2.83	-1.93	-4.56	-1.36	-0.88	-2.24	-5.16	-3.88	-9.04
$p\left(\$ / MgCO_2e\right)$		42.97			0			42.12	

Economic magnitudes in $\$ha^{-1}yr^{-1}$ and GWP in $MgCO_2eha^{-1}yr^{-1}$. Δ indicates the difference betweer conservation and conventional outcomes; π stands for (net) profits.

Results from this portion of the project indicate the following:

- Environmental and climate conditions and other risks have to be controlled for, since they add a large variability to actual yields, and therefore to profitability of alternatives.
- Managerial skills may have a large impact when computing mitigation costs, as Five Points results improve when compared to LTRAS and SAFS.
- Heterogeneity in costs structures is a way of capturing managerial skills, but there is an unobservable aspect that should be modeled stochastically.
- Although prices obtained cannot be considered relevant, the mitigation potential from alternative systems is significant.

At the time of this economic analysis, DAYCENT had not been yet completely calibrated to the main crops and practices of Yolo County. It was decided, therefore, to invest time and effort into a more accurate modeling. The new model is also intended to control for the first bullet above: a productivity potential could be obtained if the sub-model for crop growth could be used to control effectively for weather, soil, and other important factors that could not be included in the economic analysis of the experimental fields. Second, if it could be proven that predictions of farmers' behavior could be improved by embedding it in an economic model, it would be possible to incorporate bullets two and three above into the analysis of cost-effectiveness of agricultural conservation practices. Bullet four gives hope that an analysis that incorporates the complexity of environmental factors in a parsimonious and yet economically meaningful way in a crop choice model could contribute to the information currently lacking for carbon programs associated with agricultural land in California.

6.0 Implementation and Results from a Survey for Costs and Management Practices at the Field Level in Yolo County

As the results from the experimental sites showed, a sample of the population of agricultural fields in Yolo County was needed to investigate the success of payment offers to farmers to switch to GHG mitigation practices. To achieve the goal of obtaining an accurate representation of the target population and obtain detailed information on conventional and innovative management practices at the field level in Yolo County, sample design is a key issue.

The relevance of this information has to be stressed. First, it complements the currently available information on alternative practices based on budget data for experimental sites and the Cost and Return studies series carried by the Department of Agricultural and Resource Economics of the University of California at Davis.[8] The latter is a useful resource to establish guidelines to help the farming community in the production decision process, but the studies are based on assumptions describing hypothetical farm operations. The experimental sites provide an essential input to assess the effects of conventional and alternative farming systems on the environment and sustainability, but they are not meant to be managed under profit-maximizing goals, as is the case of actual farming sites. Therefore the survey conducted for this study complements those sources by offering detailed data on actual farming costs and practices for fields managed by farmers facing not just biophysical constraints, but also developing their activity under economic pressure. From the sample, estimates of population quantities—including average yields, costs, and profits—were obtained.

The study was restricted to six relevant commercial crops that are important in both their participation in typical standard rotations and in acreage in the county. This helps to sharply define the study's population. The justification for the restriction has two dimensions: computational and modeling restrictions. The impact of a given land-use on soil dynamics had to be modeled using DAYCENT analysis calibrated to particular Yolo soil properties and management. That tailored, precise modeling called for a small number of crops to begin with, and it was decided to prioritize according to the three mentioned factors: (1) acreage percentage, (2) commercial relevance, and (3) participation in standard rotations of the county. Factor (1) is intuitively reasonable; it makes sense to consider those crops with the largest physical presence in determining how a conservation policy is going to affect its distribution at the county level, and then to determine the effective carbon potential of agricultural land. Factor (3) is important not only to reduce the computational burden when simulating the soil dynamics, but also to make the analysis of the economic choices faced by farmers in Yolo feasible. Since the agronomic modeling needs some recent history on land use, the accuracy of the

[8] See http://coststudies.ucdavis.edu/current.php.

modeling was maximized by restricting ourselves to those crops that most often appear in standard rotations in the county. After consulting farm advisors and an analysis of the 2000 to 2005 Pesticide Use Report data files from Yolo County Agricultural Commissioner, five typical rotations were selected:

- Tomato-Wheat
- Corn-Tomato-Wheat
- Alfalfa-Alfalfa-Alfalfa-Alfalfa-Tomato-Wheat
- Sunflower-Tomato-Wheat
- Safflower-Tomato-Wheat

Using linear programming techniques and assuming that some fields were under continuous corn and continuous wheat, the probability of each field being in a specific rotation were computed based on the acreages of these crops calculated from the Land Use Survey of DWR (De Gryze et al. 2006). Table 6.1 shows these probabilities.

Table 6.1 Yolo County Land Use Proportions (1997)

Land Use DWR 1997	Tomato Wheat	Corn Tomato Wheat	4XAlfalfa Tomato Wheat	Sunflower Tomato Wheat Corn	Safflower Tomato Wheat Corn	Cont. Wheat	Cont. Corn
Wheat	0.05	0.09	0.15	0.09	0.44	0.19	0.00
Tomato	0.06	0.11	0.19	0.11	0.54	0.00	0.00
Corn	0.00	0.07	0.00	0.07	0.34	0.00	0.53
Alfalfa	0.00	0.00	1.00	0.00	0.00	0.00	0.00
Safflower	0.00	0.00	0.00	0.00	1.00	0.00	0.00

Source: De Gryze et al. (2006)

Note that those main rotations involve just six crops. Not surprisingly, they all happen to be highly commercial. This piece of information is also important to model the economic choices of farmers, since they not only take into account the economic relevance of crops (factor 2) in their decisions on what to plant, but also on what is suitable for their land given its recent history. Therefore, factors (2) and (3) not only help in computing the agronomic and economic models separately, but help to coordinate and link them.

To combine factors (2) and (3) with (1), the researcher team analyzed the spatial agricultural land use distribution to determine the physical relevance of crops. the study used the last field-level Yolo County Land Use Survey data developed by the Department of Water Resources (DWR),[9] which was from 1997. The main emphasis and detail of that survey is agricultural land, since urban and native (undeveloped) areas are also mapped but not in the detail of agricultural land. The DWR survey allowed us to

[9] Division of Planning and Local Assistance.

recover the spatial distribution of agricultural land use for the county. In particular, it provided a "snapshot" of Yolo County area by crops, irrigation type (irrigated or non-irrigated) and irrigation system (gravity, micro, sprinkler, or unknown) during 1997. The final form of the DWR survey is a GIS land use data file. When analyzed at the crop level, the Yolo data file shows 48 crops in its agricultural land, although the DWR survey in general covers 75 potential crops and a total of 81 subclasses of uses. Restricting the list to crops that occupy at least 1% of Yolo agricultural land, the research team found 13 leading crops whose ranking in terms of acreage is offered in Table 6.2.

Table 6.2. Distribution of Major Crops in Yolo County (1997)

Crop	Ha	%
Wheat	29,522.63	21.12
Tomatoes	21,811.07	15.60
Corn (field and sweet)	17,328.51	12.40
Alfalfa and alfalfa mixtures	13,570.94	9.71
Safflower	12,909.60	9.24
Rice	12,302.54	9.24
Walnuts	4,596.27	3.29
Almonds	3,399.54	2.43
Melons, squash, and cucumbers (all types)	3,208.43	2.30
Sunflower	2,577.13	1.84
Sugar Beets	1,998.12	1.43
Cotton	1,996.44	1.43
Mixed Pasture	1,633.09	1.17

Source: California Department of Water Resources Land Use Survey for Yolo County, 1997.

By combining the three factors, it was determined that the six relevant crops are ones shown in bold type in the above table: wheat, tomato, corn, safflower, rice, and sunflower. Alfalfa was included in carbon sequestration policies because it is grown in multiyear rotations. The agronomic model takes into account its rotational role and incorporates it in the modeling of the soil dynamics.

There are two other important aspects to mention with respect to the study's population. The population units were not farmers, but agricultural fields. An integrated assessment approach, where the agronomic modeling has to be coupled with an economic model, called for the units of the population to be identified with precise soil characteristics. Also, for aggregation purposes based on soil characteristics and land use, field units facilitate the construction of a carbon sequestration supply curve by agricultural land for the whole county. The fact that the distribution of agricultural fields in Yolo from the 1997 DWR land use survey showed that most of the fields (97%) had a single use made the field unit even more convenient. This simplifies spatial aggregation, because the field could be identified with a unique land use.

The second relevant aspect of the study's population was that it was restricted to those fields managed by the same farmer during the last four years. This restriction enabled the study to focus on owned land rather than leased land. It is expected that a conservation policy based on green payments for crop/management choice based on the amount of carbon that can be sequestered would induce a change in the way a farmer leases land and manages the land on his or her property. By restricting the study to fields consistently managed over time by the same farmer, the effect of the policy on how the farmer manages his or her portfolio of land is ignored. However, restricting the population to fields under the same management for a period of several years allowed the study to focus on the economic and biophysical potential of the policy as a long-term instrument. Future research could address the net effects of the same policy when tenancy is included as an endogenous variable in farmers' decision.

6.1. Stratification in the Sampling Design

As noted in the introduction, the assessment of the efficiency of carbon sequestration by changing agricultural land activity as a climate change policy mainly depends on:

- The soil characteristics of the land in the region.[10]
- The land use: crop choice and the management alternative applied on each field.

These two aspects are characterized by being highly diverse in California and in Yolo County, and at the same time are clearly intertwined. The sampling design built for this study allowed us to get samples that reflect those characteristics of the population. To cope with the heterogeneity in soil characteristics within the county, the research team followed a strategy to obtain a representative sample for the soil characteristics of the region under study. For that reason, it was decided to perform random sampling in the last stage of the design, where fields are sampled. Since soil characteristics can be obtained at a very detailed level via the USDA's SSURGO database for the county, it was assumed that random selection of fields and soil characteristics was the best way to obtain a representative sample of soil properties and microclimates. The idea behind this was that random draws were obtained from a large population, which results in representative samples in the infinite population context and avoids contributing to selectivity biases through researcher subjectivity.

However, at the farm/land-use level it cannot be assumed that there is an infinite population. During 2005 there were only 224 conventional farmers using technology to cultivate the six crops surveyed in this study. This was even more evident for the small population of non-conventional technology farmers; during 2005 there were only 41 growers of the six crops of interest. Although the ultimate goal was to sample fields, not

[10] Among all the environmental and physical factors that affect agricultural carbon sequestration, soil is perhaps the most determinant for the success of carbon sequestration as a stable policy for GHG mitigation. Besides, as it will be seen, other relevant biophysical factors are taken into account in the integrated analysis approach, which combines agronomics and the economics.

farmers, the number of fields it was possible to survey from the same farmer was limited to one or two, due to time and economic constraints when collecting the sample.[11] It could be said that the precision of the integrated assessment, which builds on specific farm sites comes at a cost: namely, the challenge to obtain a representative sample given the time and economic costs to obtain observations with highly precise information.

The role of sampling design is then crucial to overcome this restriction in the diverse landscape of Californian agriculture, both in terms of land use and soil types. This study's sampling scheme was adapted to over-represent those farmers that were applying "innovative" management practices (i.e., using conservation tillage, cover cropping or crop under organic standards) and compare them to conventional farmers who were not using those conservation practices. The purpose is to compare revenues and cost structures among the two groups when determining the financial incentives conventional farmers require for adopting mitigation practices. It will also provide a basis to determine the actual crop and innovative management combinations currently undertaken in the county. This will be important to reduce the dimension of the choice set of a conventional farmer.

Farmers using either organic, winter cover crop, and/or conservation tillage are a minority. Data from the farmers already using carbon-sequestering practices are crucial to model and statistically explore the response of conventional farmers to carbon sequestration payments. For that reason, all of them were included in the sample. In that way it was possible to capture all the available variation in the small subpopulation of farmers (not fields) for conservation practices. The research team was naturally led to stratify the population into well-defined groups of units (by land-use). At the same time there were two subpopulations or strata by management: fields for each of those strata under conventional and innovative management. Survey designs that employ stratification typically result in smaller variance estimates than those corresponding to alternative designs (see Cochran 1977, Chapter 5). In particular, stratification is more effective in decreasing variability when sampling units are more similar within the strata than between them.

There are two options when using stratification: (1) adopt a random stratification, that is, a method by which sample units are selected at random within each stratum, independently of the selection of units within other strata; or (2) assign varying probabilities within each stratum. This study used a combination of the two, because of the double stratification (by crop and management).

Note that under stratification, the selection of units is partially controlled, in the sense that the probabilities of selection might depend on the stratum being drawn from. Also,

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[11] Although the sample was efficiently designed to be answered in 30–40 minutes, the sample design also tries to account for the fact that a farmer rarely would offer more than 1 or 2 observations.

since units are being separated by strata, the number of potential combinations of n units that can be selected from the population are being reduced, when compared to random sampling. This is equivalent to saying that the probabilities of selection of a subset of units of the population are being increased, just by simply separating the units in domains of study or strata. But defining strata in terms of crops and management the study is selecting only the preferred units within the potential samples, and contributing to the goal of obtaining useful data given the restrictions and aim of precise farm site information.

In addition, an advantage in terms of statistical inference is that empty strata cells are avoided in the management/land-use matrix in which the population units are distributed. Finally, the stratification has an additional advantage in this application: it provides a basis to extend the data set to similar counties in the future. Controlling for the change in crops being produced, it would not be difficult to simply "load" an enlarged data set into the integrated assessment procedure, with few additional methodological adjustments. In reality it would only add another stage to the sampling design, one in which several counties are sampled, and then proceed in exactly the same way.

6.2. Sample Design and Estimation of Population Quantities

Efficient surveys require that the design leads to optimum results with minimization of the total loss in terms of cost and mean square error. The main steps followed to achieve that aim were as follows:

- To define clearly the objectives of the study.
- To define clearly the population under study.
- To determine the sampling frame and sampling units.
- To select the proper sampling design.
- To organize the field work.
- To summarize and analyze the data.

The first task was to select agricultural fields from Yolo County, to jointly study economic, managerial, and agronomic characteristics at the field level. The research team used satellite images that overlapped graphical information to identify in the most accurate way the location and field boundaries, as shown in Figure 6.1.

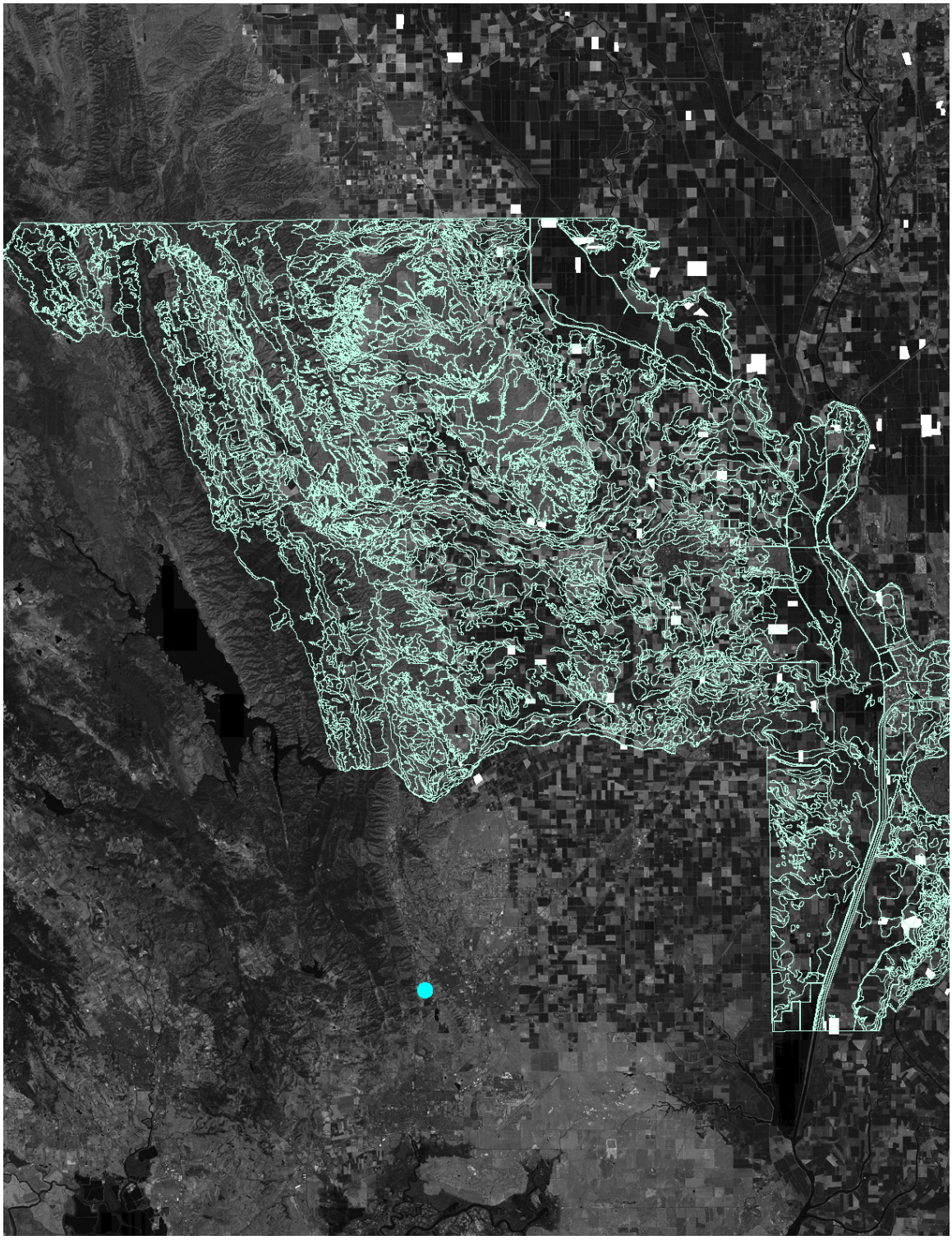

Figure 6.1. Yolo soil classifications overlaid on land use by field

Source: SSURGO

The population under study was agricultural fields, which in year 2005 were used to grow, under certain management practices, the main six commercial crops involved in representative crop rotations of Yolo County: wheat (Wh), tomato (To), corn (Co), safflower (Sa), sunflower (Su), and rice (Ri). The management practices referred to are conventional management (Conv), reduced and conservation tillage (RT), cover cropping (CC), and organic systems (Org). However, it was not possible to distinguish a priori who was actually applying those three conservation practices. This chapter considers a broader division of the population by management practices: the conventional and the non-conventional.

The sample frame was constructed from the following registries and lists of growers:

(1) The Pesticide Use Reports (PUR) for years 2000–2005 carried out by the county's agricultural commissioners. The PUR datasets are collected annually to record details of all pesticide applications on agriculture farming land in the entire county. Each report provided the following data:

- Crops planted from 2000 to 2005 in a given field identified within a township range section (TRS).[12] It also included the name of the pesticide used and the amount applied, but this information was not used in the sampling design.
- The farmer operating on each field from 2000 to 2005 and contact details of the farm: name and location of the farm where the pesticide is applied, including address, phone numbers, ZIP code, and other information.

Thus the PURs were used to construct the part of the sample framework for farmers using conventional management, who compose most of our population in Yolo County.

(2) The California Certified Organic Farmers (CCOF) directory for certified organic growers. This listing includes all of CCOF's organic farmers, processors, handlers, packers, and retailers, as well as CCOF-certified organic crops, livestock, processed products, and organic business services. It offers a special chapter for Yolo County that helps to identify the population in the study area. The directory facilitated information on the name and location of the certified organic farmer and the crop organically produced by each farmer.

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[12] Although the registry offers an identification for the specific site within the TRS where the field is located, the maps of field boundaries used to build the registry was made available neither by the Department of Pesticide Regulation (DPR) nor the Agricultural Commissioner office, although there is a Field Borders Development project being conducted and maintained in Yolo County that would offer GIS data that could be overlapped with soil maps for the county. Therefore, only the field up to the TRS level could be identified, which required the research team to use satellite imagery to make the surveyed farmer identify the specific field. This is not important for the selection of units for the sample, but it is for recovering the field's soil characteristics.

This information was used to construct the organic farmer sample frame. Although information in the CCOF includes the address of these farmers, it does not offer information on the location of each farmer's individual fields. For the units coming from that registry, the surveyors went down to the field selected by the farmer with GPS devices to generate its mapping in the research team's own GIS data.

(3) Private farm advisors' lists of growers using cover-cropping and reduced till were used to complement the list above. It was found that most organic growers in the CCOF also use cover crops.

The following text describes the selected sampling design. Figure 6.2 presents it schematically.

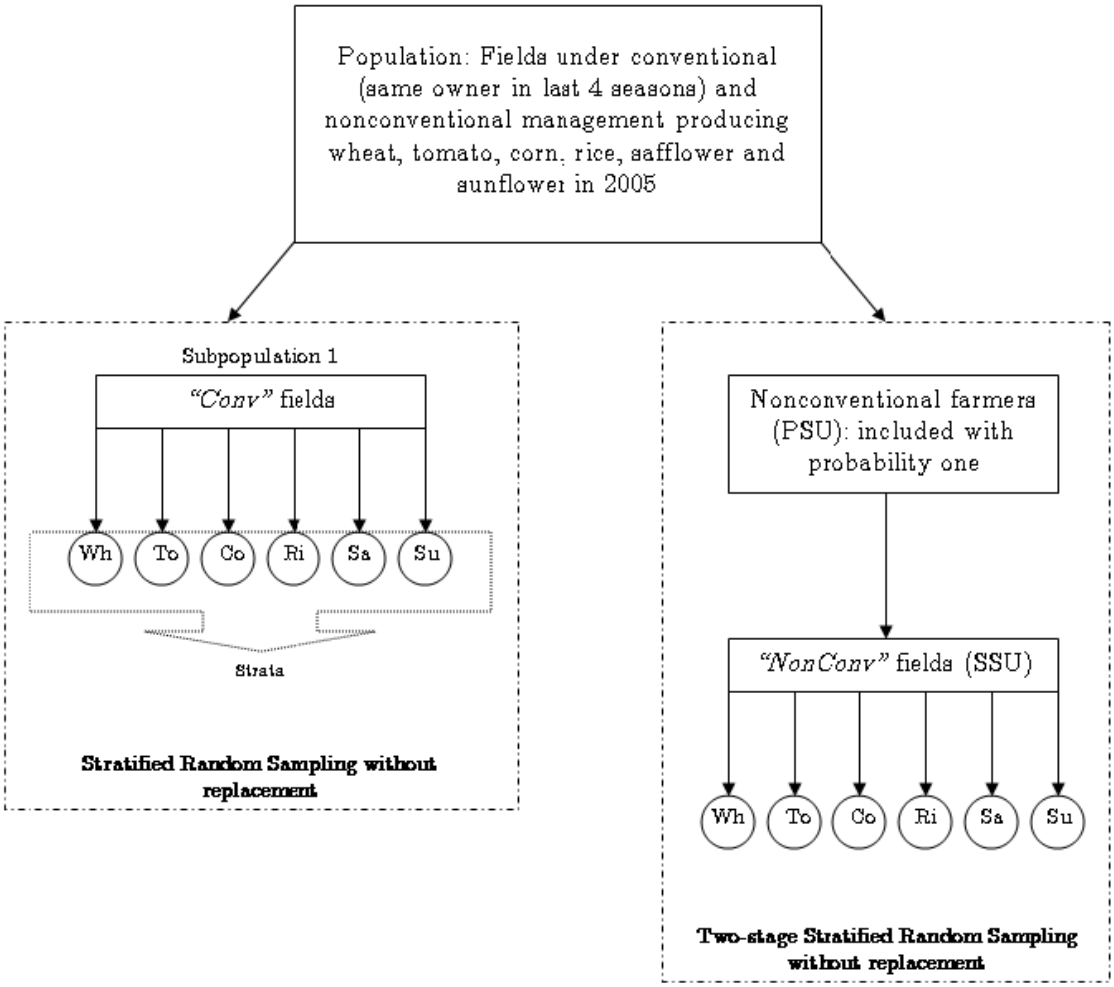

Figure 6.2. Stratified Sampling Design

Clearly, the auxiliary information divides the population into two subpopulations. For conventionally managed fields, the field devoted to a crop during 2005 could be located up to the TRS level from the PUR database. That information was overlapped with a satellite image of the area from 2001, which offered a clear depiction of fields and their boundaries. To precisely identify the field and its boundaries, since they might change from 2001 to 2005, the questionnaire was accompanied with a map of the portion of the satellite photo corresponding to the TRS. The farmer was presented that map and he identified the field and its actual boundaries for 2005.

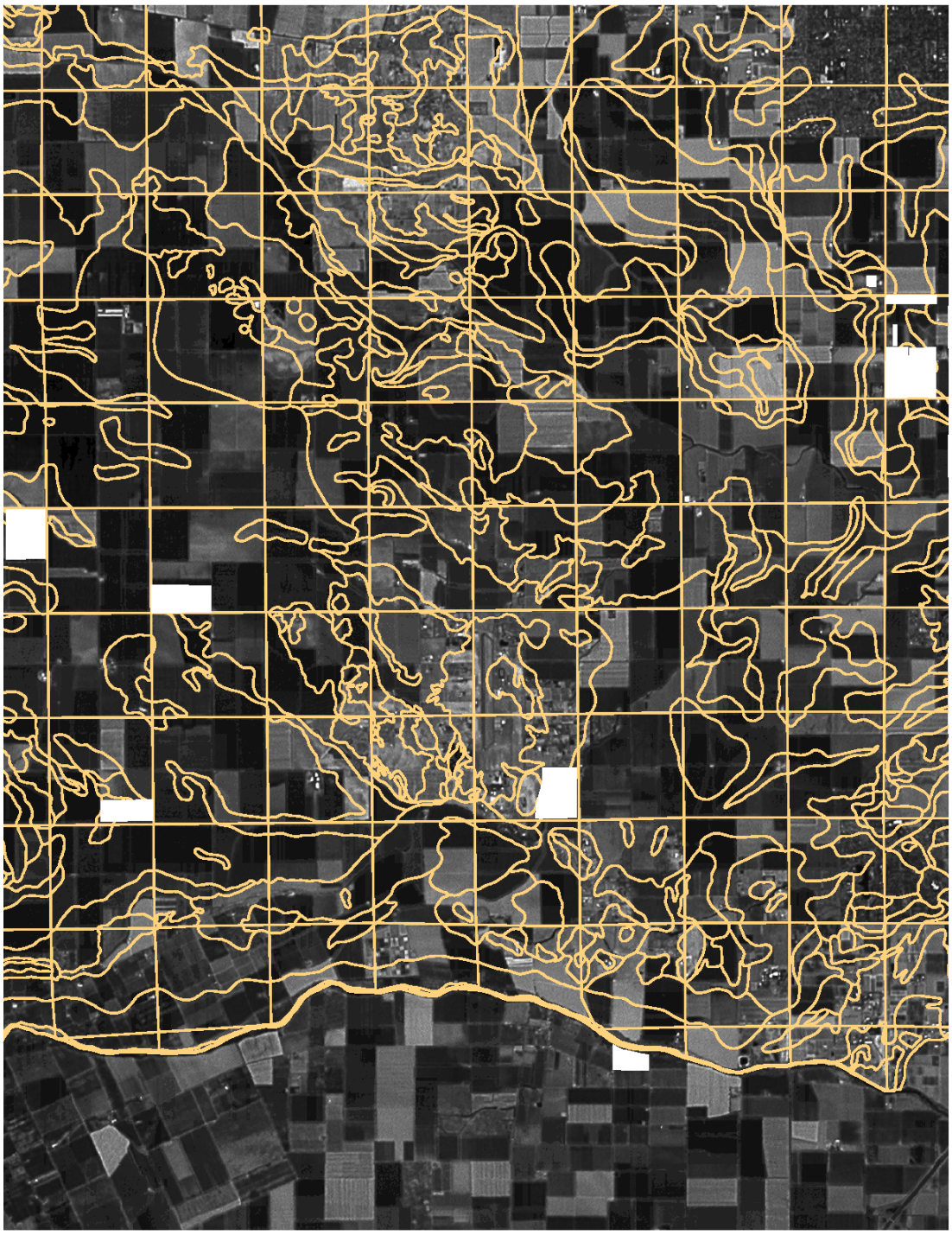

Figure 6.3. Field image by town range section grid

Source: SSURGO

Because fields were being sampled rather than farmers, each unit fell into only one of the domains. The conventional domain contains 405 units based on the PUR. On the other hand, the non-conventional subpopulation is composed by 54 growers of the crops of interest and 198 fields in Yolo County. From the sources of information about

innovative farmers, the location of their business address in Yolo County could not be identified.

Since the field under unconventional management could not be identified first, before the farmer, as is done for the conventional management, the farmer was asked to pick a field randomly among those where he planted the selected crop. Many growers had appropriate fields in some neighboring county. Thus, some of the surveyed fields are outside Yolo County's boundaries. This does not pose a serious problem, since could the research team could control for the soil and biophysical conditions using SSURGO and other sources for the neighboring counties. Some of those farmers grew the crop of interest or simply randomly chose the field. There were, in total, 322 fields managed by conventional farmers, and the total number of fields of those farmers were reported, regardless of the county.[13] This number of fields was known only after the survey was undertaken. All identified growers were included in the survey and asked how many fields they had under a specific crop and management.

For non-conventional fields, the study proceeded in two stages. First, all farmers applying non-conventional management practices were included. Thus, the non-conventional farmers are the primary sample units (PSU) from which were sampled the fields without replacement, the secondary sample units (SSU). Therefore the farms identified as being under non-conventional management were always sampled; but the SSU were sampled with equal probability and without replacement. The inclusion of all the non-conventional farmers was justified because the distribution of management practices in the area of study is very skewed, with the conventionally managed fields contributing overwhelmingly to the population. Data on those fields under conservation management is important to obtain robust estimates in the discrete choice model for management and crop. Finally, it offers a unique piece of information on detailed costs/structures not yet available and studied for the study area.

Sixty conventionally managed fields and 54 non-conventional fields were surveyed. The number of conventional farmers surveyed represents a 15% of the population of fields, but involved a 36% of the farmers of the region growing the six crops of interest. Further, many of the farmers were growing one or two of the six crops during 2005. It was crucial to obtain detailed information on management and economic and physical inputs at the field level, and at the same time to capture heterogeneity in farmers' preferences. Thus, the preference was to have a larger number of farmers screened, although it was apparent that this would translate into a smaller number of fields surveyed, since it was not realistic to expect more than one or two fields from the same farmer to obtain detailed information at the field-level. The size in acreage and number of fields on the surveyed crop are described in Table 6.3.

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[13] The study found that while wheat, tomato, and sunflower are mostly located in Yolo County, safflower and corn are mostly located outside the county's boundaries. A balanced result was found for rice.

Table 6.3. Primary Survey – Yolo County 2005

	$Conv$	$\overline{Conv}$	$\overline{Conv}_{Yolo}$	units
Planted acreage (2005)	97,681	108,178	74,871	acres
Number of fields planted (2005)	1,347	1,790	1,277	
Total Crop Acreage (2005)				
• Wheat	1,278.65	741	526	acres
• **Tomato**	373	577	514	acres
• **Corn**	445	208	5	acres
• Rice	2,205.2	1,260	268	acres
• Safflower	582	380	171	acres
• **Sunflower**	270	445	199	acres
Number of fields for crop (2005)				
• Wheat	38	78	73	
• **Tomato**	53	55	48	
• **Corn**	28	28	3	
• Rice	133	80	12	
• Safflower	36	31	16	
• **Sunflower**	15	50	46	

Source: DWR Land Use Survey for Yolo County, 1997.

The fourth column is included to indicate how farmers in the innovative farmer population are distributed by the six land uses and acreage within Yolo County. The third column provides the information for all fields in that subpopulation, even if they happened to be located outside the county boundaries. It is also important to note that although this table is just offering sample statistics, it is also a full census of the innovative population; the values in Table 6.3 are also population quantities for that group.

The sample frequencies per crop and per management are represented, respectively, in Figure 6.4 and Figure 6.5.

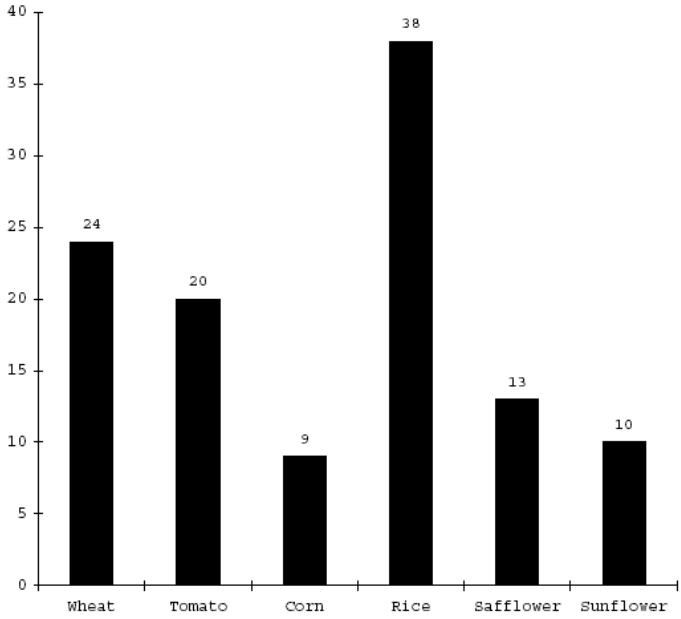


Figure 6.4. Crop sample frequencies

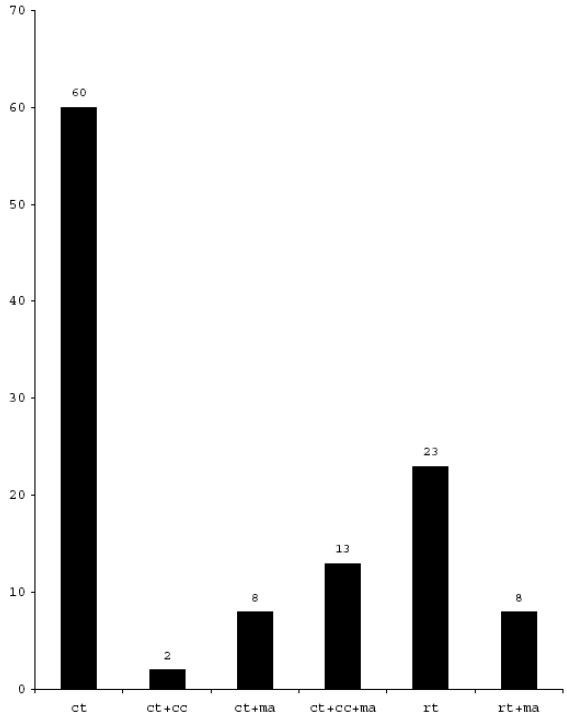


Figure 6.5. Field sample distribution by management classification

Note: ct = conventional tillage; ct+cc = conventional tillage and cover cropping; ct+ma = conventional tillage and manure (no inorganic fertilizers); ct+cc+ma = conventional tillage, cover cropping, and manure (no inorganic fertilizers); rt = reduced till; and rt+ma = reduced till and manure (no inorganic fertilizers)

The main goal for studying the conventionally managed fields was to obtain a representative sample in terms of soil types for each land use. Therefore, a random stratified sampling was used. The population of conventionally managed agricultural fields was subdivided into 6 strata; one for each crop. The strata are indexed with {1; 2; 3; 4; 5; 6} where

$$z_2 = \begin{cases} 1 & \text{land use is } Wh \\ 2 & \text{land use is } To \\ 3 & \text{land use is } Co \\ 4 & \text{land use is } Ri \\ 5 & \text{land use is } Sa \\ 6 & \text{land use is } Su \end{cases}$$

Population and sample sizes are given in Table 6.4.

Table 6.4. Stratified sample by crop

z_2	Wh	To	Co	Ri	Sa	Su	
N_{z_2}	107	162	16	45	9	66	$N = \Sigma_{z_2} N_{z_2} = 405$
$W_{z_2} = \frac{N_{z_2}}{N}$	26%	40%	4%	11%	2%	16%	
n_{z_2}	13	6	6	21	8	6	$n = \Sigma_{z_2} n_{z_2} = 60$
$w_{z_2} = \frac{n_{z_2}}{n}$	22%	10%	10%	35%	13%	10%	
$\frac{n_{z_2}}{N_{z_2}}$	12%	4%	38%	47%	89%	9%	

Since the PUR database provides enough auxiliary information to group the population of conventionally managed fields into strata, it is possible to adopt the classical approach of randomization inference (where sample size is considered fixed) and use an "optimal" 15 allocation of units across strata by taking into account monetary and time constraints to administer the survey, and at the same time try to minimize the variance of the estimators across strata. However, the multi-purpose nature of the survey made it difficult to follow the "optimal" allocation principle in a simple and clear manner. One

contemplated solution was to use non-linear programming to minimize the overall variance of estimators for the different population quantities involved. However, because it was important to contact farmers before the next season began, it was decided that researcher judgment would suffice. Although this is not the most scientific way of approaching the problem, it is the standard procedure in practical applications involving many objectives under tight time constraints.

After defining the strata per land-use, the research team performed a random sampling without replacement within each. The estimates of the population quantities of interest are offered in Table 6.5, with the corresponding sampling errors. As the table shows, the stratified design tends to obtain estimates with lower variance for the whole population, as expected. Within strata, higher variances were obtained for the estimates; the only way to achieve a higher efficiency would be with a lager sample size. Despite the study's small size sample, average yields appear unbiased, as they are very close to the average county yields obtained from official sources.[14]

[14] Agricultural Commissioner of Yolo County data, USDA county production data.

Table 6.5: Conventional fields' population estimates of relevant economic variables

	Wh	*To*	*Co*	*Ri*	*Sa*	*Su*	Population
Mean no. of fields planted	16.31	57.5	24.83	16.52	19.375	23.16	34.33
	[18.13]	[30.89]	[11.87]	[12.53]	[21.85]	[8.41]	[27.50]
Mean acreage of fields	98.36	62.16	74.16	105.01	72.75	45.00	74.40
	[70.65]	[17.61]	[7.36]	[53.15]	[40.84]	[37.68]	[6.17]
Proportion of conventionally managed acreage in farm	0.98	0.83	0.49	0.83	0.94	0.81	0.86
	[0.03]	[0.25]	[0.4]	[0.28]	[0.17]	[0.32]	[0.002]
Proportion of organically managed acreage in farm	0.00	0.002	0.32	0.13	0.00	0.013	0.031
	[0.00]	[0.006]	[0.45]	[0.24]	[0.00]	[0.02]	[0.007]
Proportion of conservational till acreage in farm	0.01	0.16	0.28	0.019	0.06	0.17	0.11
	[0.036]	[0.25]	[0.34]	[0.06]	[0.17]	[0.32]	[0.04]
Mean yields (tons/acre)	2.25	35.66	4.81	3.72	1.03	0.69	-
	[0.50]	[5.31]	[1.27]	[0.90]	[0.39]	[0.4]	-
Mean revenues per acre	230.26	1742.67	500.29	919.07	258.38	1027.97	1052.87
	[53.99]	[259.77]	[138.94]	[167.76]	[70.94]	[534.92]	[53.94]
Mean variable costs per acre	128.36	786.29	279.22	276.50	101.05	225.68	429.17
	[46.51]	[352.79]	[80.45]	[135.57]	[33.77]	[58.05]	[56.80]
Mean profits per acre	101.9	956.48	221.07	642.56	149.33	802.29	623.71
	[74.47]	[511.68]	[139.35]	[191.26]	[94.02]	[530.88]	[88.87]

Sampling errors between brackets.

The non-conventional population is composed of 54 farmers, who are identified through the CCOF directory and the personal lists from farm advisors.

Sometimes the CCOF identified a farmer as growing one or several crops of interest, but after contacting them it was discovered that they had not planted one or more of them in 2005. Also, the number of fields in each farm was not available before the survey. Therefore, a stratified two-stage sampling was applied. The use of an embedded two-stage sampling was required due to the lack of an accurate directory for fields under non-conventional management. This problem needed to be addressed by the sampling design since the subpopulation under conventional management was composed of fields, and any meaningful comparison of the two groups requires consistency in the final units being sampled.

To thoroughly study the population of non-conventional fields, those organic farmers identified as producing any of the six crops of interest during 2005 were included. This allowed the identification, without sampling error, of the total number of fields in this management category. In other words, the sample frame for this subpopulation was updated since all farmers were included. This procedure was valid because the population was small. Only one secondary unit/field was selected from each primary unit/farmer, because of the difficulty of getting the questionnaire completed and to minimize the non-response error.[15] That is, the entire population of primary units was being observed, but only a fraction of secondary units were observed. Since the primary units are individual farmers, with management skills homogeneously applied to their fields, this extension of the population is strengthened in the primary stage, with a consequent gain in precision.

The stratification by crops on top of the two-stage sampling for alternatively managed fields could seem an excessively complicated design, however, that is the most common design in large-scale surveys. The uniqueness of this design is simply that the whole population of primary units was sampled. Because the sampling within each stratum is independent, it is a valid approach. In particular in this scheme, within each stratum {1; 2; 3; 4; 5; 6}, all the primary units are selected and each of them is further sub-sampled also independently. The notation followed is:

- Let z2 stratum contain Nz2 farmers/primary units, each with Mz2 fields/secondary stage units.
- The corresponding sample amounts are nz2 and mz2 .

Table 6.6 offers the specific numbers for the population and sample sizes.

Table 6.6. Survey populations

z_2	N_{z_2}	n_{z_2}	M_{z_2}	$M_{z_2 Yolo}$	m_{z_2}
Wheat	11	11	78	73	11
Tomatoes	13	13	55	48	13
Corn	3	3	28	3	3
Rice	17	17	80	12	17
Safflower	6	6	31	16	6
Sunflower	4	4	50	46	4
Total	54	54	322	198	54

[15] A very few number of growers decided not to participate.

A complete sample was used in the first stage (with replacement across strata).

From it the research team obtained unbiased estimators of the characteristics of the total population and used them to construct a table with subpopulation estimates of relevant quantities, which are presented in Table 6.7.

Table 6.7. 2005 Yolo County survey – mean yields, revenues, and non-conventional technology

	Wh	*To*	*Co*	*Ri*	*Sa*	*Su*	Population
Mean no. of fields planted	8.00 [2.84]*	4.20 [2.08]*	9.30 [6.01]*	4.71 [0.98]*	5.16 [1.34]*	12.63 [5.36]*	6.16 [1.21]*
Mean acreage of fields	65.63 [7.57]*	44.40 [12.67]*	69.33 [41.26]*	74.15 [9.06]*	63.41 [11.82]*	111.25 [22.99]*	66.54 [7.03]*
Proportion of conventionally managed acreage in farm	0.70 [0.13]*	0.18 [0.07]*	0.62 [0.25]*	0.47 [0.10]*	0.64 [0.15]*	0.61 [0.19]*	0.49 [0.05]*
Proportion of organically managed acreage in farm	0.13 [0.11]*	0.99 [0.34] *	0.33 [0.27] *	0.35 [0.09] *	0.27 [0.16]	0.032 [0.02]	0.43 [0.06] *
Proportion of conservational till acreage in farm	0.29 [0.02] *	0.37 [0.01] *	0.24 [0.02] *	0.20 [0.01] *	0.18 [0.01] *	0.34 [0.04] *	0.27 [0.04] *
Mean yields (tons/acre)	2.05 [NR]	18.93 [NR]	5.17 [NR]	2.88 [NR]	0.88 [NR]	0.70 [NR]	- [NR]
Mean revenues per acre	205.03 [NR]	24,129.59 [NR]	945.13 [NR]	972.80 [NR]	211.31 [NR]	1,135.74 [NR]	5,611.94 [NR]
Mean variable costs per ha	118.33 [NR]	5,356.17 [NR]	268.12 [NR]	601.12 [NR]	95.27 [NR]	198.53 [NR]	1,294.08 [NR]
Mean profits per ha	86.70 [NR]	18,773.42 [NR]	344.02 [NR]	704.67 [NR]	116.03 [NR]	937.21 [NR]	4,317.86 [NR]

Sampling errors between brackets. "[NR]" indicates not reported.

*Indicates the population standard deviation is reported when no sampling error applies.

There are some relevant facts about the "innovative" population that should be mentioned:

The tomato stratum in the innovative population is extremely diverse. The results are difficult to compare to the same land use stratum for the conventional population. The main reason is the heterogeneity in the varieties they grow. While almost without

exception the tomato growers in the conventional sample produced processing tomatoes, organic growers diversify by producing for the fresh market as well as the processing market. The yields for the fresh market tomatoes are much lower, since they are different varieties and selectively harvested. At the same time, the organic prices they obtain cannot be directly compared to the ones that, on average, a conventional processing tomato grower obtains. The price premium tends to more than compensate the much lower yields when computing revenues.

The variety in alternative practices is another characteristic of the innovative population (see Figure 6.7). Probably a post-stratification strategy could be useful to obtain more precise estimates about crops. A post-stratification[16] was used to analyze the sequestration potential of each alternative management practice in the next section.

[16] Post-stratification is used when there are some substantive categories for the researcher in the population, but she or he cannot determine before the survey to which category each unit belongs. With post-stratification sampling, weights are adjusted so that the sum of the weights within each post-stratum is equal to the respective post-stratum size. The result is, in general, smaller variance estimates.

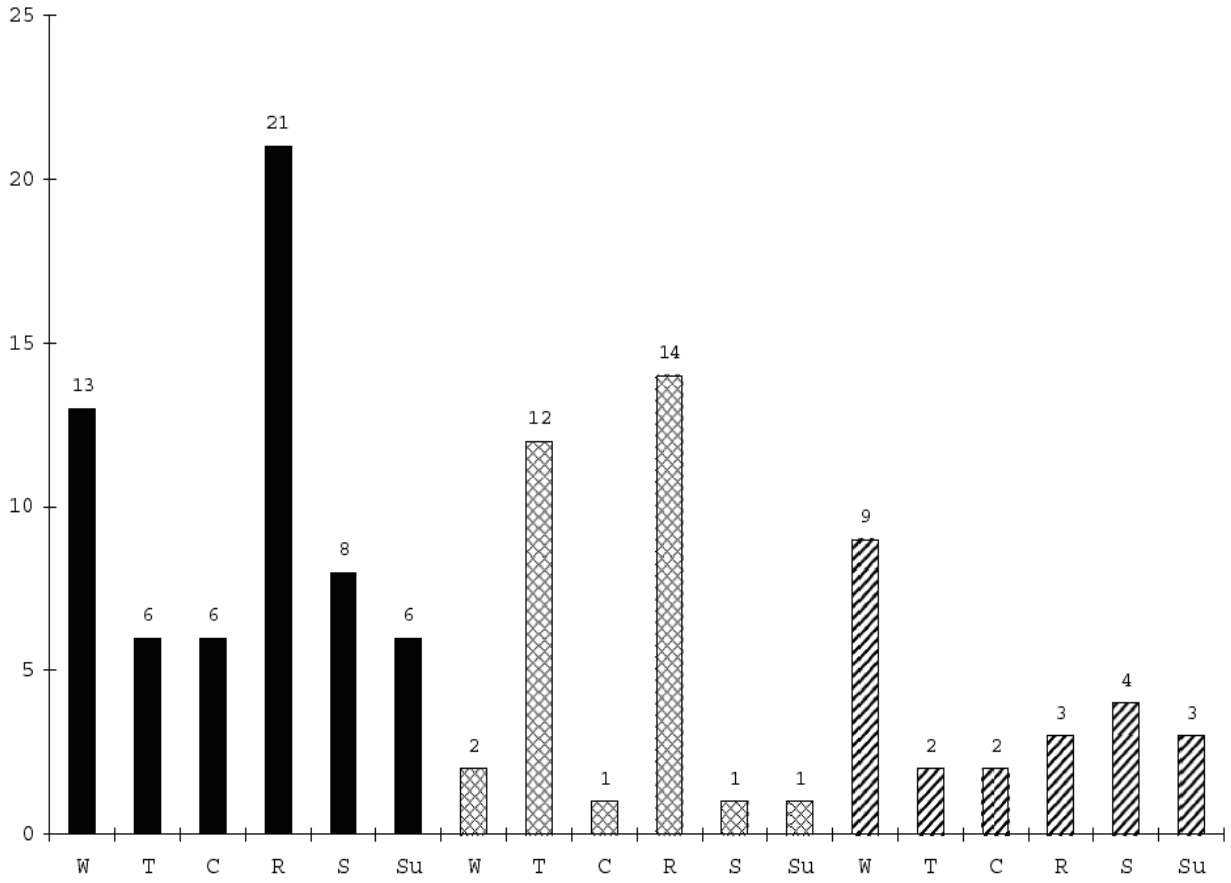
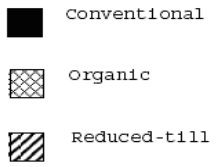


Figure 6.6 Sample management technology



W	**Wheat**
T	**Tomatoes**
C	**Corn**
R	**Rice**
S	**Safflower**
Su	**Sunflower**

A comparison of the population quantities estimates for each subpopulation shows that conventional practices are applied in larger farms and fields, for all crops. It is interesting to find that farmers in Yolo specialize in technologies and tend to show strong preferences on conventional practices for certain crops more than for others. For instance, a conventional (average) farmer growing wheat, rice, safflower, and sunflower on his or her farm has a very small proportion of fields devoted to alternative practices for those crops. An explanation for this is to consider that, on average, farmers are still considering and investigating how those alternative managements could work on a few

fields, while continuing to grow most fields under conventional practices to secure production with their current skills. The same can be said of organic tomato growers, who devote very small land areas to conventional practices, but not so for the corn, rice, safflower, and sunflower, which are cultivated with conservation practices in 40% of the fields. Wheat is a remarkable case of a crop that shows more resistance to alternative practice adoption. Table 6.5 and Table 6.7 show that under non-conventional practices, yields are always lower (with the exception of corn; although the small sample of that stratum may be responsible for the small difference). As remarked above, the yields for organic tomato growers are about a half of those obtained by conventional ones, due to the different varieties and to the selection of only the best fresh tomatoes in the harvest.

Profits show that use of alternative practices does not mean necessarily make less money, except for wheat or safflower. Overall, for the innovative group, revenues tend to be larger for all crops (but wheat), as are costs. The profits reflect that on average in 2005 applying conservation practices in production resulted in higher returns per acre over variable costs. However, the mean hides the fact that, among this study's observations, the profits among organic growers are much more volatile than the ones obtained under conventional management. Also, it is likely that the observations for alternative practices are "contaminated" by the land effect; namely by the self-selection of specific types of crops that are easier to adopt conservation practices, making adoption sometimes unprofitable. This is taken into account in the next section, which discusses controlling for different types of soil and using DAYCENT.

6.3. Coupling GWP and Productivity Potentials With Survey Data

The DAYCENT model analysis for soil dynamics was tailored to encompass both county level and field-level soil and management specificities. This allows the research team to compute a plausible global warming potential for alternative practices on each field given the management and crop history observed for each sampled field. It also allows the team to perform an analysis along the lines of the one previously performed for the experimental sites, but now using farmers' actual data on management and costs.

The 405 units of the conventional population were modeled, using the land history provided by the PUR. The population estimates were then used for the average total variable costs and constructed estimates of profits for each unit by multiplying price per the yield obtained of the growth plant sub-model in DAYCENT[17] of the crop grown in 2005 under each of the management observed in the survey. Those alternative practices are shown in Reduced tillage (RT).

[17] This sub-model was calibrated with county data to obtain yields that, adjusted to the soil characteristics in the population units, are comparable to those obtained at the county level.

- Reduced tillage and organic ferlizer (RT+MA).
- Conventional tillage and organic fertilizer (CT+MA).
- Conventional tillage and cover crops and organic fertilizer (CT+CC+MA).
- Conventional tillage and cover crops (CT+CC).

Analyzing the survey data, the research team confirmed that a pure reduced-till system, RT, must be treated differently than organic systems as CT+CC+MA or CT+MA. While in these two latter systems the total variable costs are significantly higher than those for conventional farmers, RT adopters tend to report lower total variable costs. This is due to lower fuel expenses and labor hours involved in ground preparation and during the season in general. The difference with these units is found in the machinery costs, since the purchase of new machines and the adaptation of tractors are necessary. Therefore the research team computed from the observations an estimate of the machinery costs for RT that can be attributed to that concept by year and acre, with an annualized average value of $49 per hectare, and included it in the computations of the cost per unit of that particular management. This also applied to RT+MA.

There is also a price premium for organic growers, from which RT adopters do not benefit. The price premium can be quite large, and that reduces the unit cost of carbon sequestration for some crops in certain soil types, as is shown in Figures 6.7 through 6.12, below. The reason for farmers' reluctance to adopt carbon conserving practices is probably because the expected positive effect of that price premium from adoption is offset by the agronomic suitability of the practice, the use of farm land as a whole, behavioral patterns, or market characteristics.

Combining the survey information with DAYCENT modeling resulted in cost curves for carbon sequestration from adopting alternative practices for the target population. Figures 6.7 through 6.12 compare the carbon sequestration cost-effectiveness of the different alternative practices for each crop. Within each crop, only those alternatives used by the sampled units were analyzed, since cost data was needed to estimate the price per unit of Mg CO_2-eq. Those costs were computed with

$$c_m(soil) = \frac{\Delta\pi_m(soil)\frac{\$}{ha}}{area\text{ha} \times \Delta GWP_m(soil)\frac{\text{Mg}CO_2\text{e}}{ha \times yr}}$$

[Equation 13]

where Δ indicates the difference with respect to the estimated quantities for conventional management. Thus for each alternative management (m), one can compute

$$\pi_m = p_m \times y_m^{DC} - TVC_m$$

[Equation 14]

For each population unit using GIS, the dominant soil type and the crop history since year 2000 were identified, and therefore it was possible to compute the per-unit carbon

sequestration cost for each management, soil, and land-use history, since DAYCENT calculated an expected yield, y_m^{DC}.

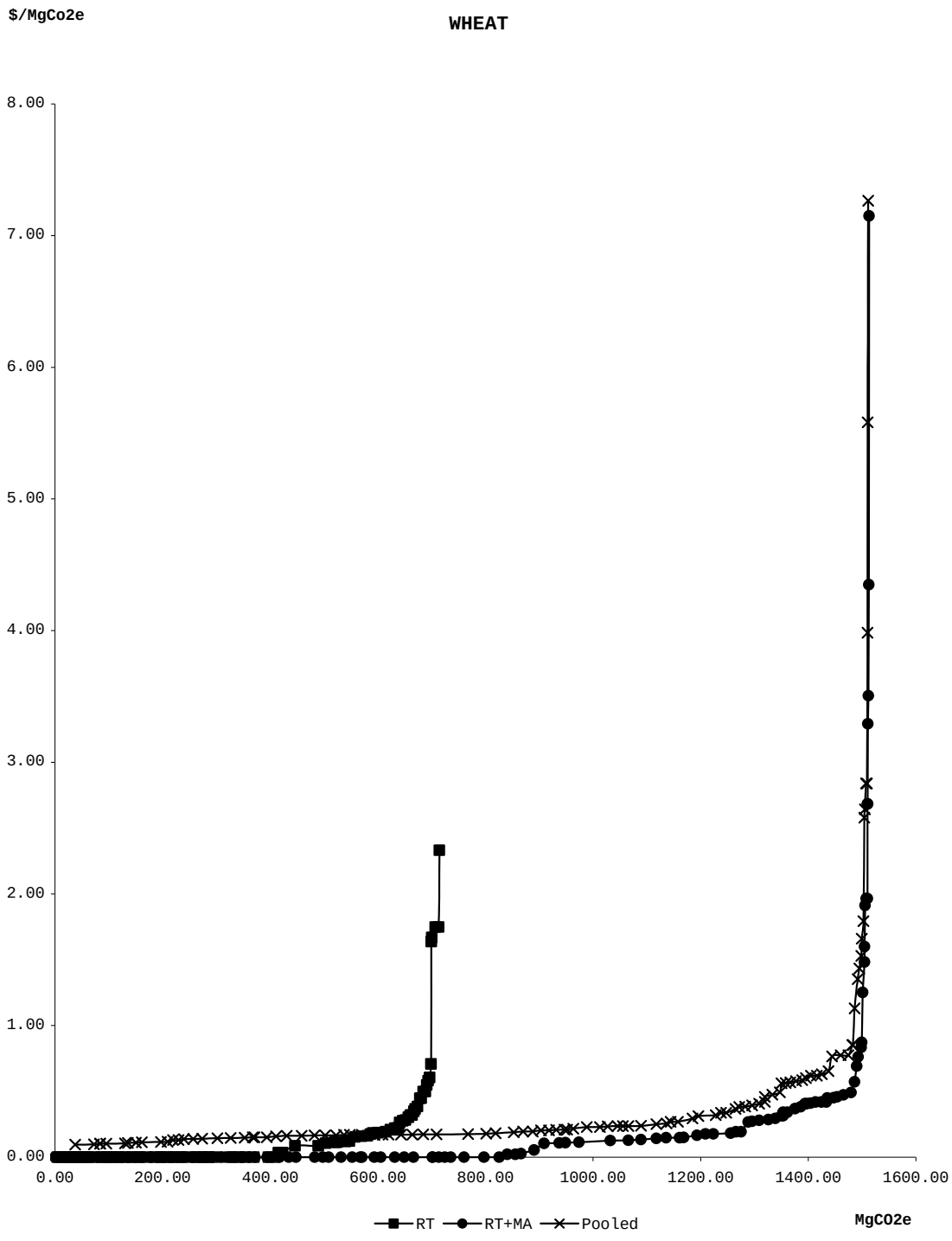


Figure 6.7. Wheat carbon sequestration response functions

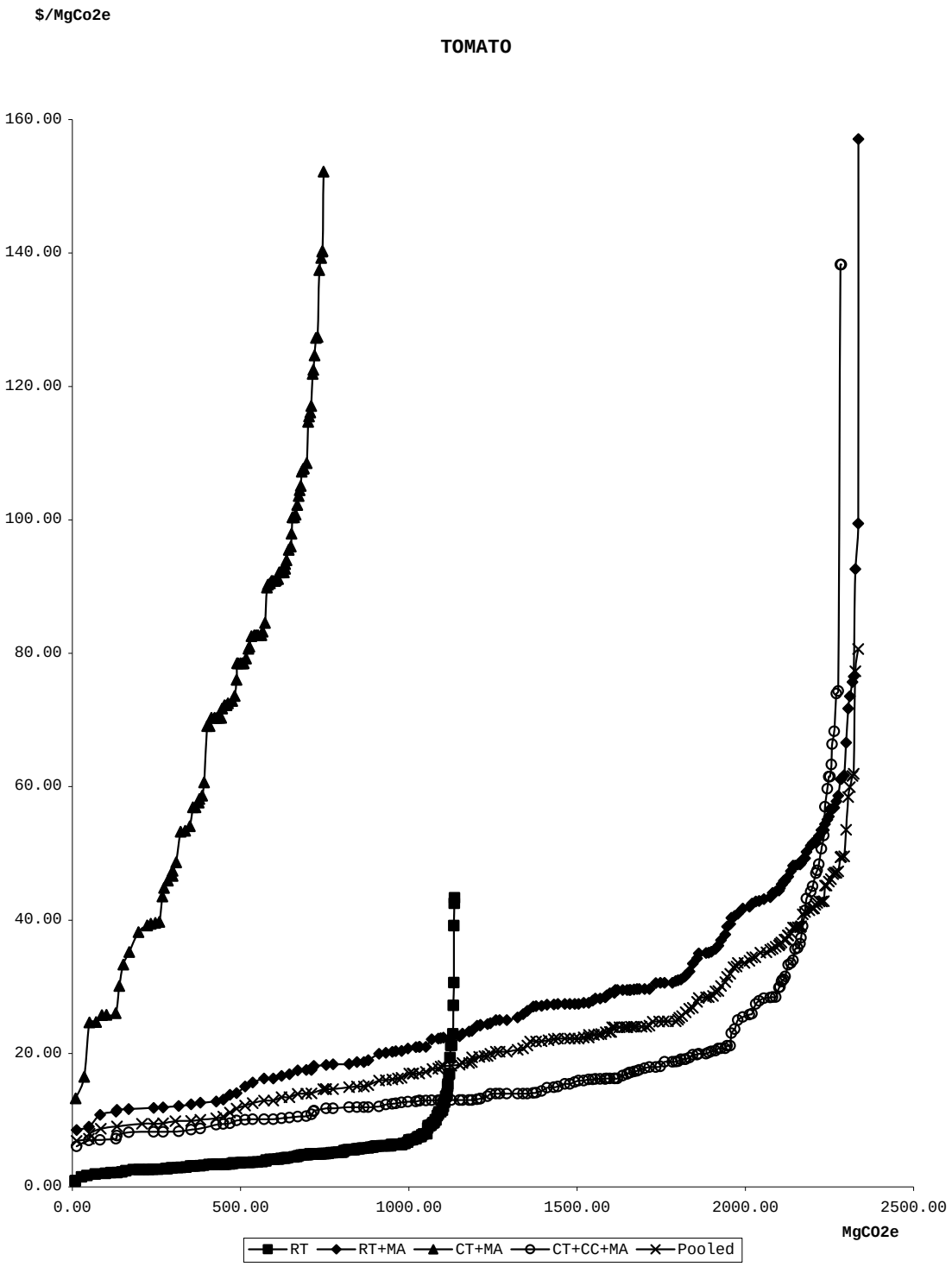


Figure 6.8. Tomato carbon sequestration response functions

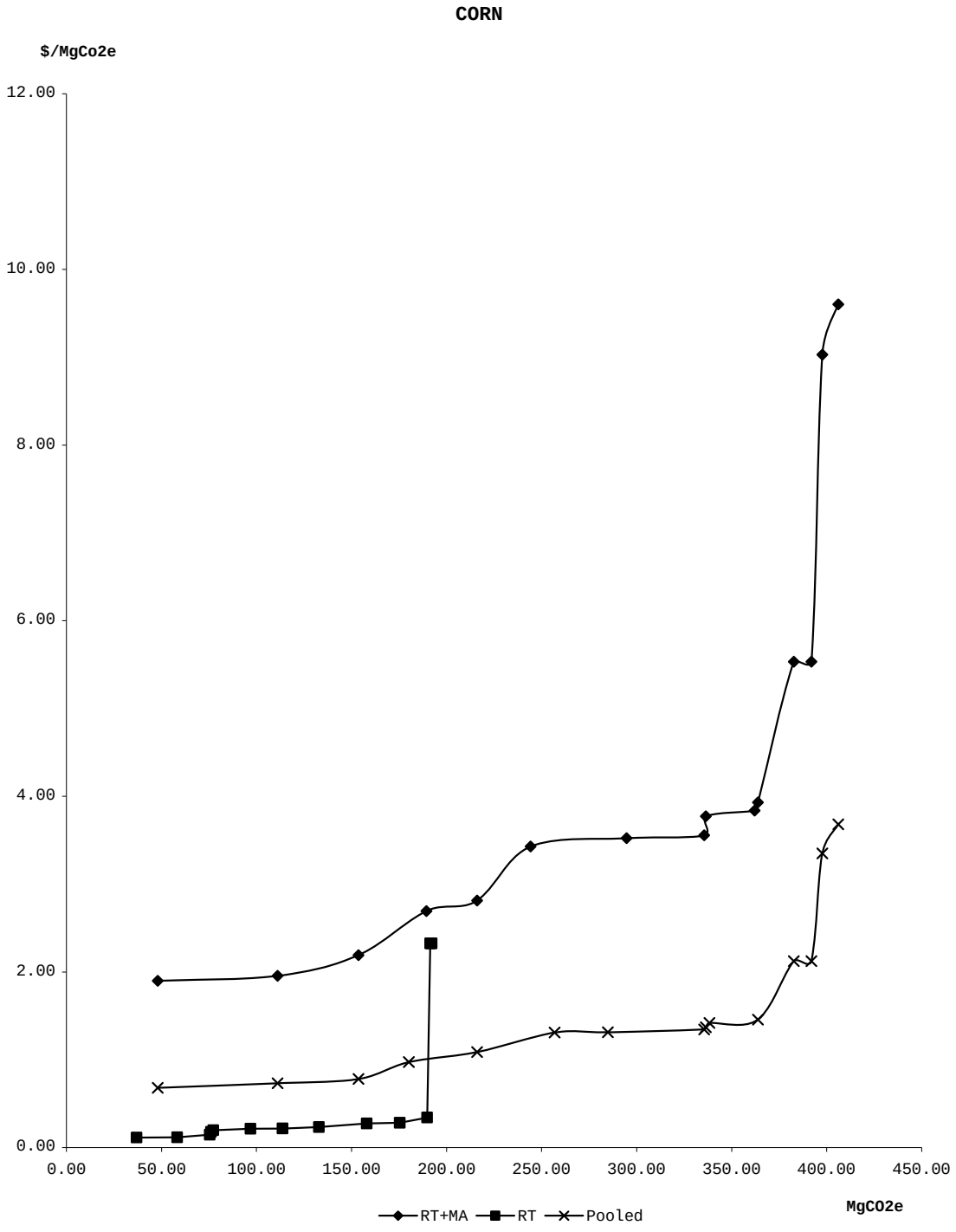


Figure 6.9. Corn carbon sequestration response functions

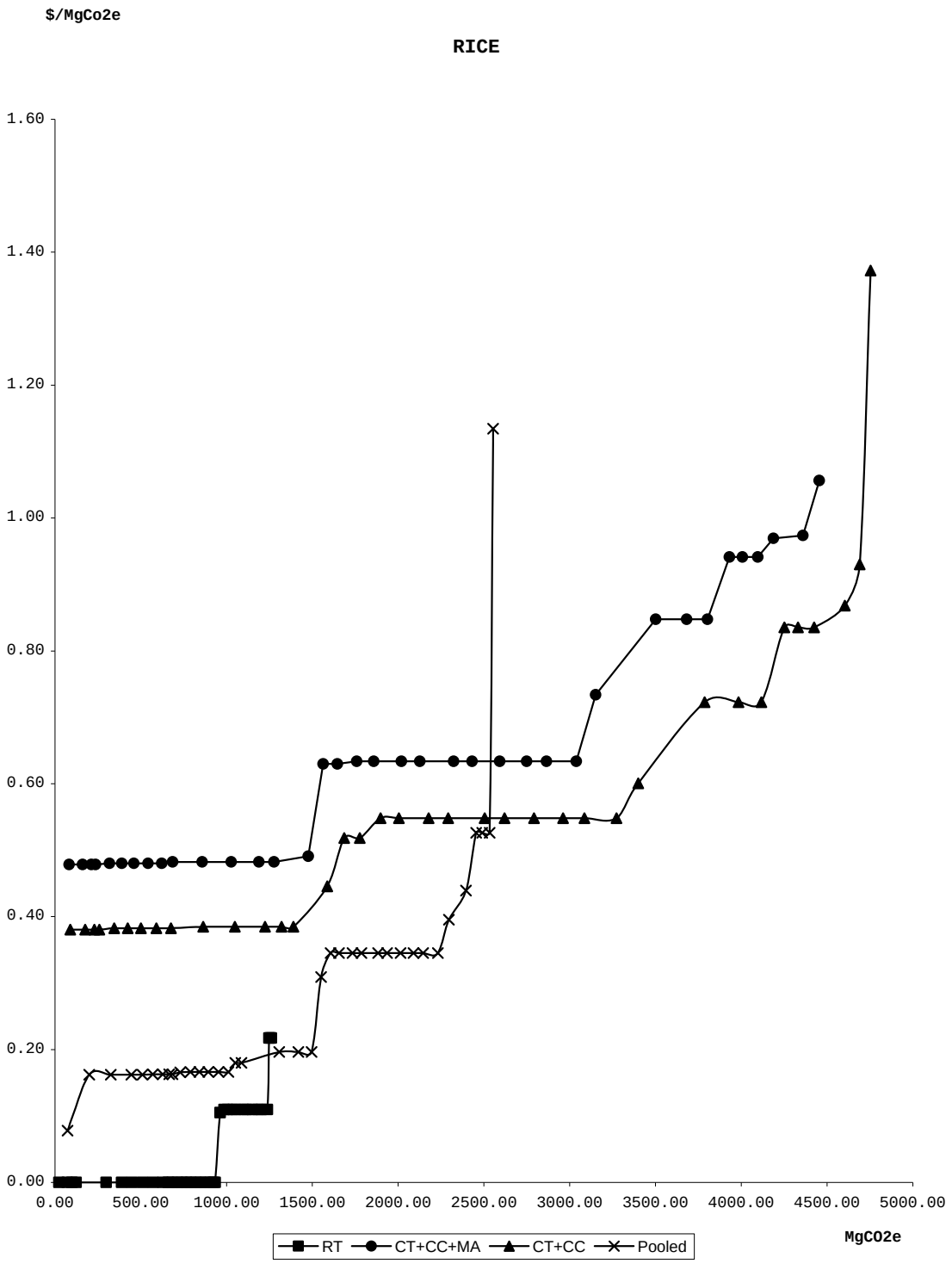


Figure 6.10. Rice carbon sequestration response functions

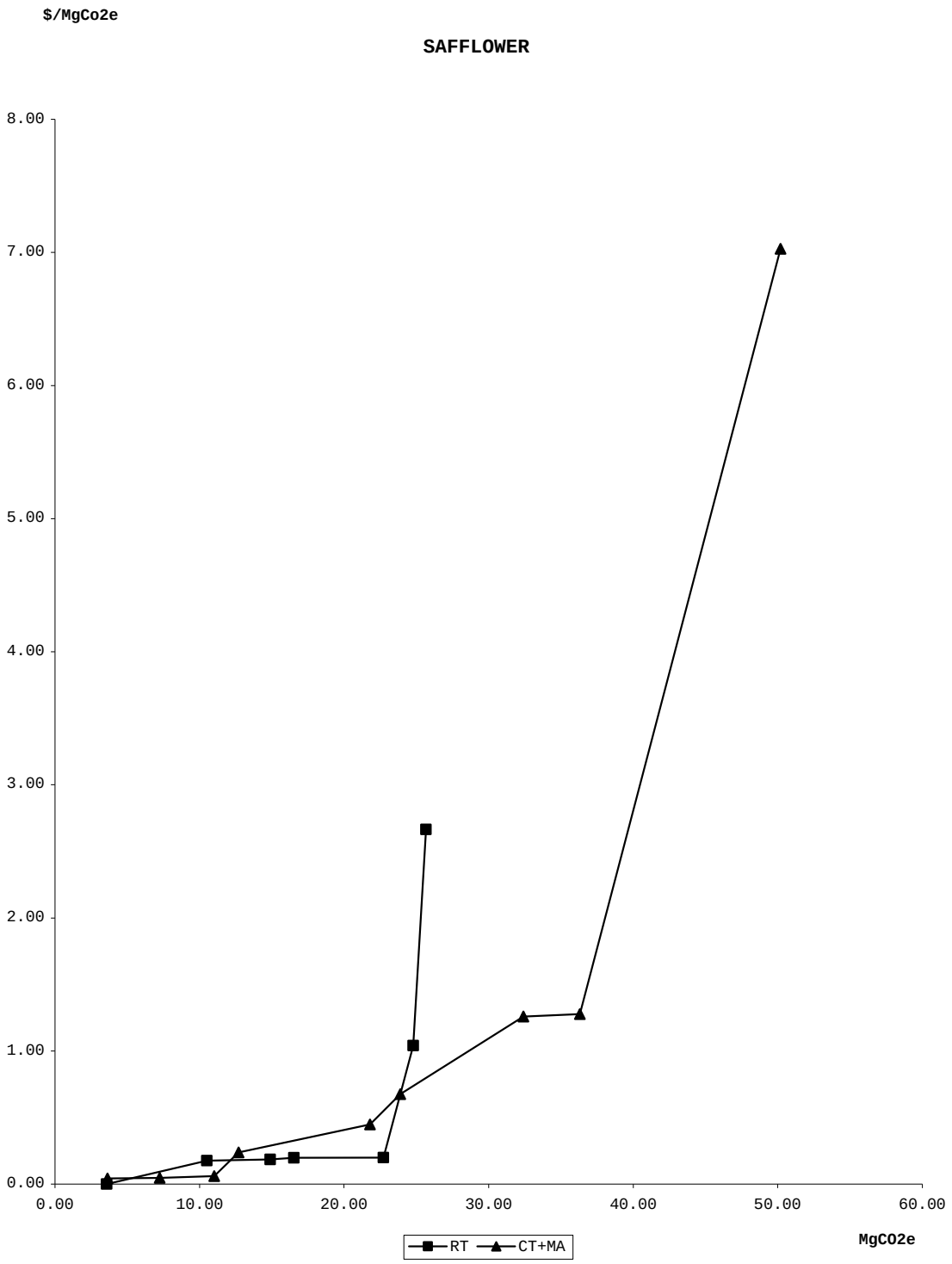


Figure 6.11. Safflower carbon sequestration response functions

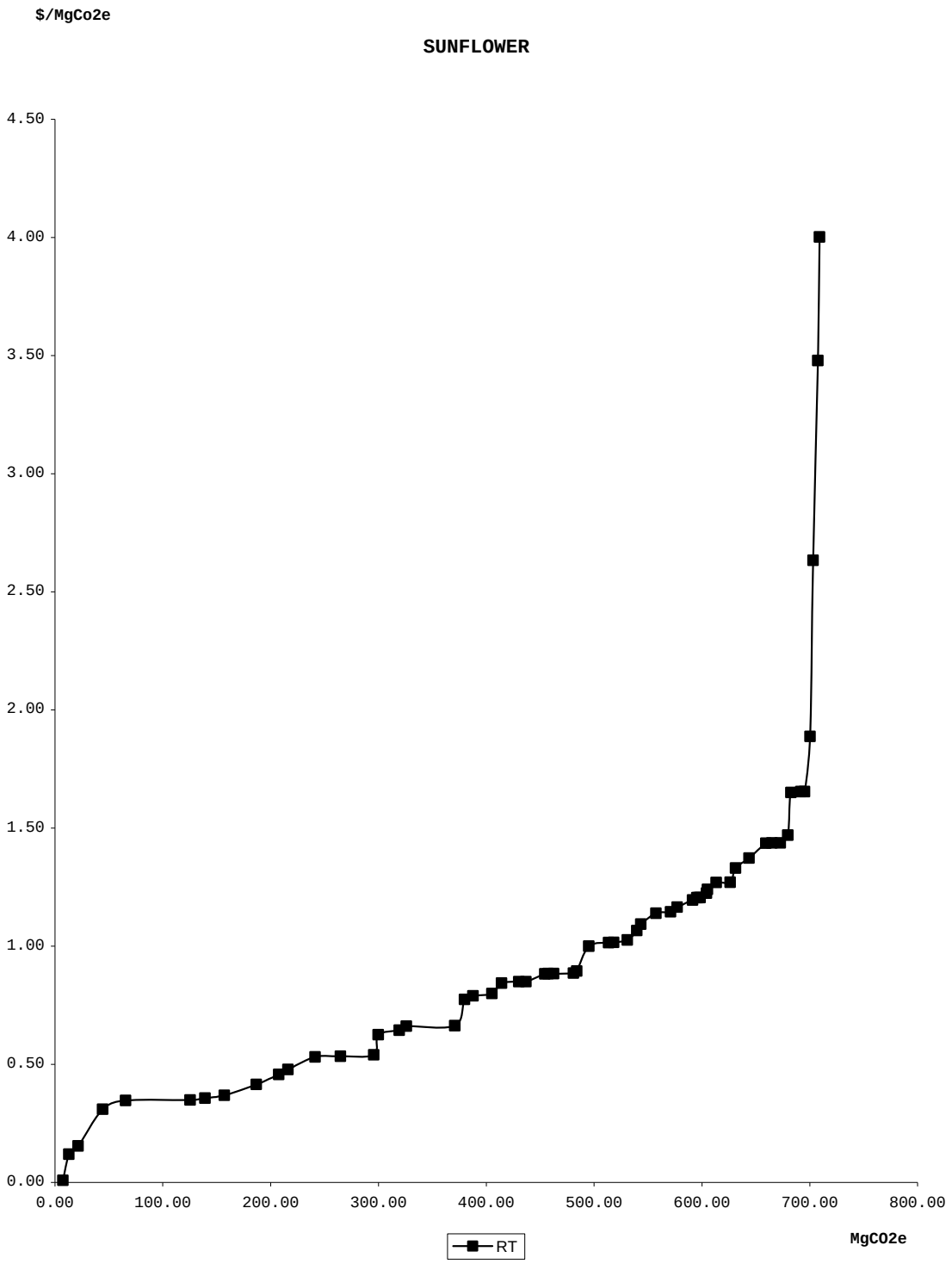


Figure 6.12. Sunflower carbon sequestration response functions

Figure 6.6 through Figure 6.12 show that the cost-effectiveness of alternative management varies largely within each crop. Table 6.8 summarizes the maximum storage capacity of each land use based on the area it occupied in 2005.

Table 6.8. Maximum carbon storage capacity

z_2	Ha	$Maximum\ MgCO_2e$	$Ratio\ MgCO_2e/ha$
Wheat	3,064.55	1,600	0.52
Tomatoes	4,633.97	2,500	0.54
Corn	408.37	450	1.1
Rice	2,159.46	5,000	2.31
Safflower	228.78	800	3.5
Sunflower	2,241.31	1,600	0.71

Finally, safflower, corn, and tomato are chosen as examples to illustrate the heterogeneity in soil types conditional on the soil type used. In Figures 6.13 through 6.15, each rectangle pattern represents a soil type. The same soil types appear several times, showing a different cost that depends on the field's cropping history. This indicates the importance of focusing on fields managed by the same manager in the last seasons, since a different soil type (considering microclimate conditions equal) can be much more costly to sequester carbon. This adds complexity to carbon program implementation, since direct carbon measurement and monitoring is costly. For instance, for tomatoes, which occupy the largest area among all land-uses, a very large number of soil types are involved in the construction of the costs curves above. However, sunflower and corn occupy a similar area, and the latter shows a smaller variation in soil types (see Figure 6.13 through Figure 6.15). This shows that either farmer preferences or soil suitability, or both, are combined to result in a more "inelastic" soil supply curve.

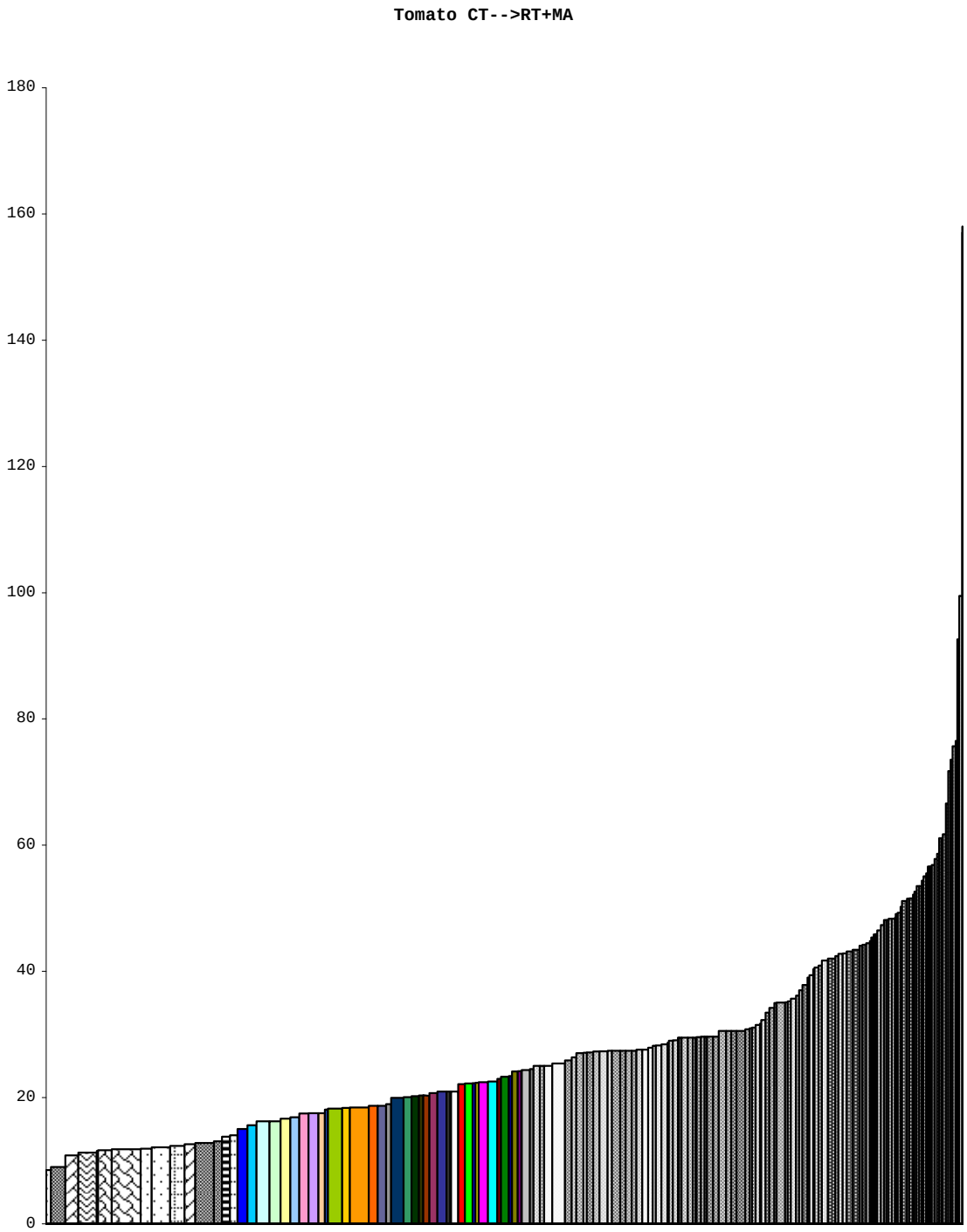


Figure 6.13. Tomatoes – carbon sequestration by soil class

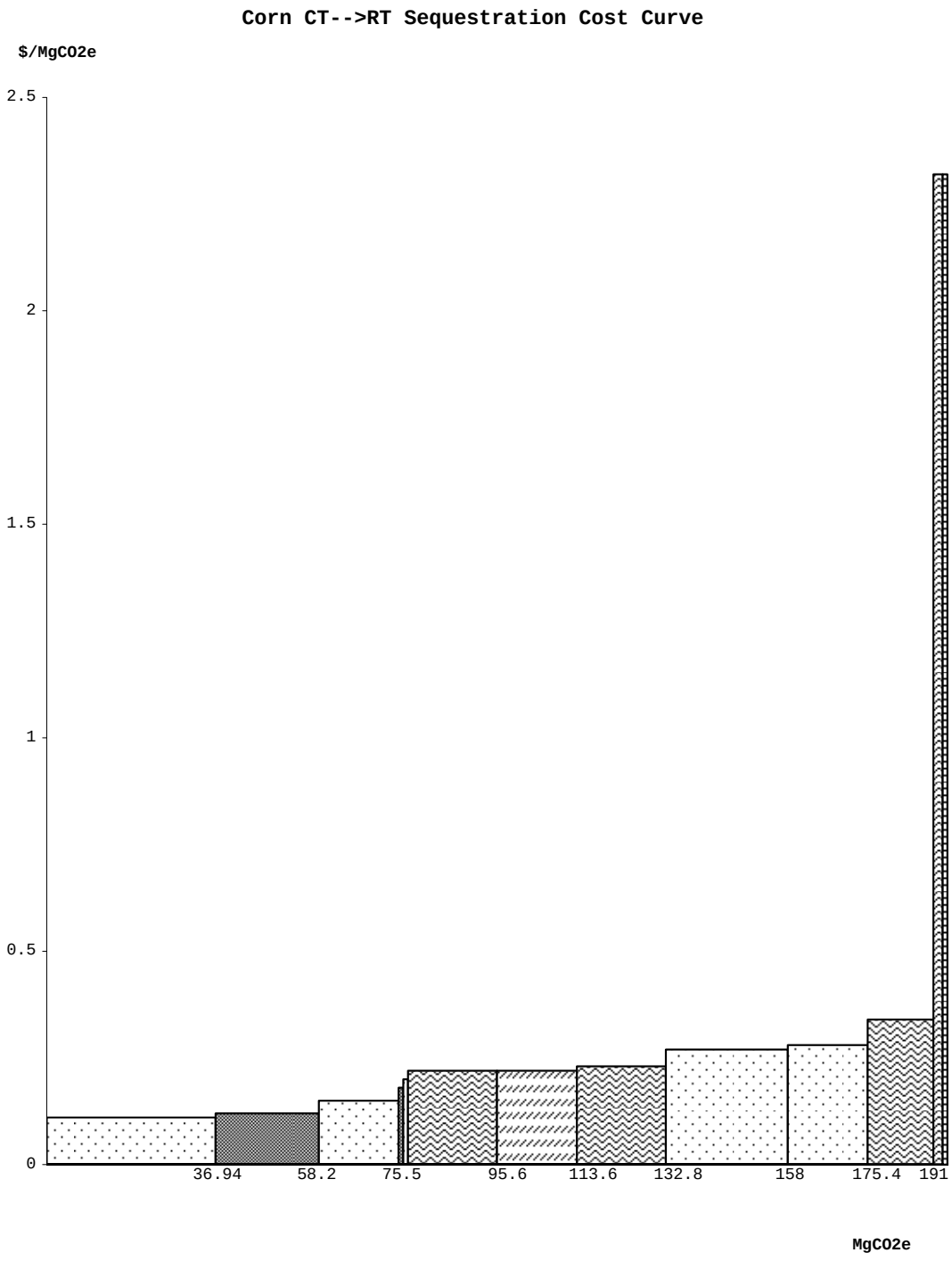


Figure 6.14. Corn – carbon sequestration by soil class

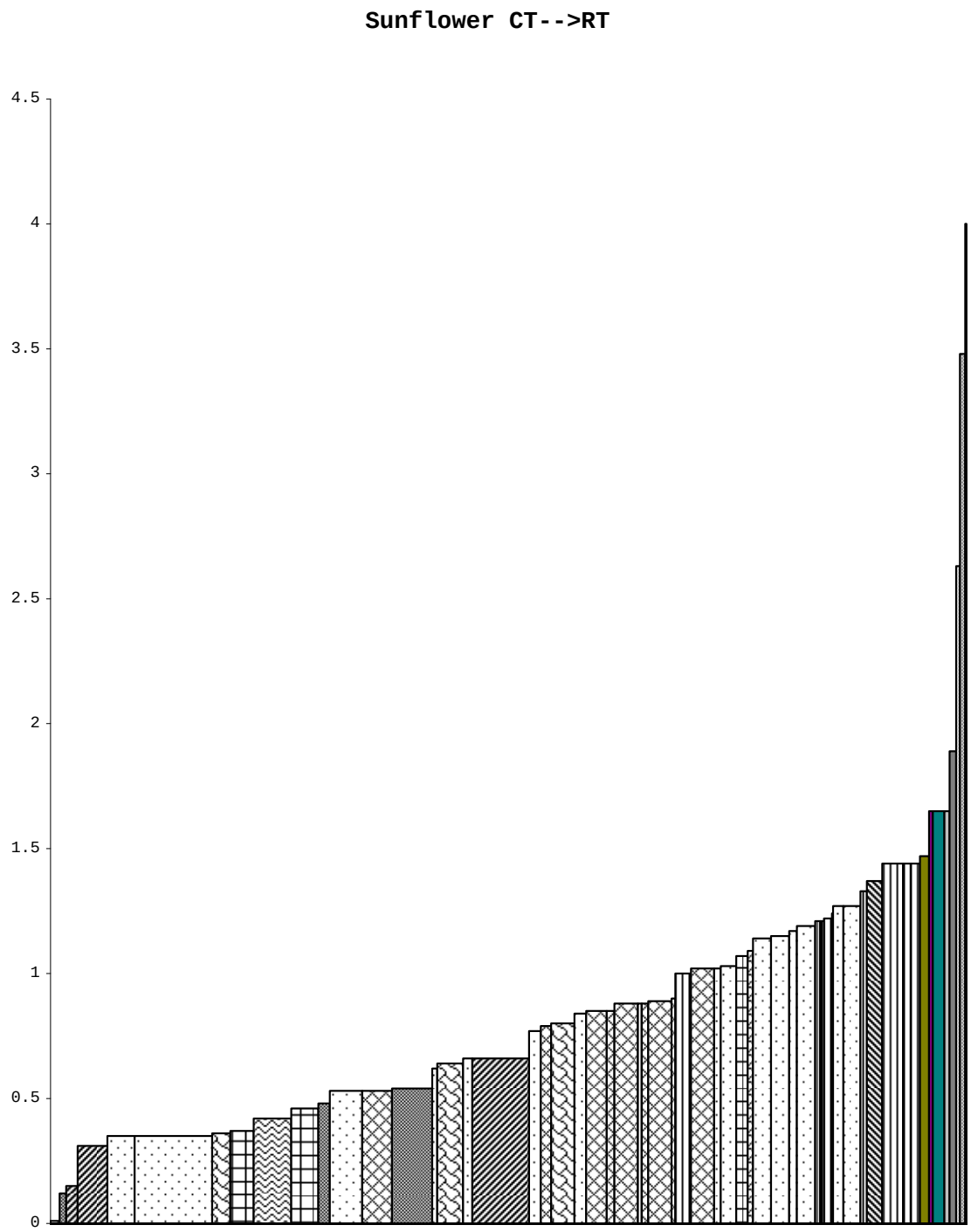


Figure 6.15. Sunflower – carbon sequestration by soil class

6.4. Modeling and Predicting Farmers' Choices

Since observable behavioral aspects such as experience in alternative management and unobservable aspects such as skills or beliefs are important to determine how likely it is that a farmer will choose to adopt a particular combination of crop and management, the final step in this investigation was to incorporate them into the analysis.

To study the combined effect of economic and agronomic factors and the distribution of skills and preferences across farmers, the research team constructed an econometric model which statistically adjusts how farmers compare alternative crop-management combinations. To do this, the survey data was extended using DAYCENT to perform hypothetical assessments about the different alternatives a Yolo County farmer faced in 2005 in a given field. That is, if conventional wheat was applied in a particular field, that sample unit was modeled in DAYCENT to assess the productivity potential of different land uses. Essentially DAYCENT predicts the yields under different crops and practices. The effort produced a matrix of 18 alternatives: 6 crops combined with three management alternatives. Those three management alternatives were conventional management, reduced-till, and organic systems. Cover cropping was not introduced separately because no case of conventional tillage and cover cropping was observed; only organic systems made use of cover crops.

The resulting econometric model offered the following features:

(1) The crop and management choices are jointly made. This design allows for correlation between crops and management (see Figure 6.16).

    Although the diagram suggests that the decision was modeled in two steps (first the farmer chooses the management and then chooses the crop) this was not the case. What the diagram represents is the way the correlation structure was modeled in the decision process across management and crops. Within each nest, there are substitution patterns (i.e., the decisions are correlated), whereas across nests (management) they are not. The empirical model predicted farmer behavior quite well, with an accuracy of 73%. The researcher team considered that this simplification in the correlation structure of the decision process was a good approximation.

(2) The farmer compares the profitability of each alternative and chooses the one that maximizes the probability of the corresponding profit. It is important to note that the productivity comparison estimated by DAYCENT allowed the expansion of the 114 field sample to 2052 observations.

Figure 6.16.

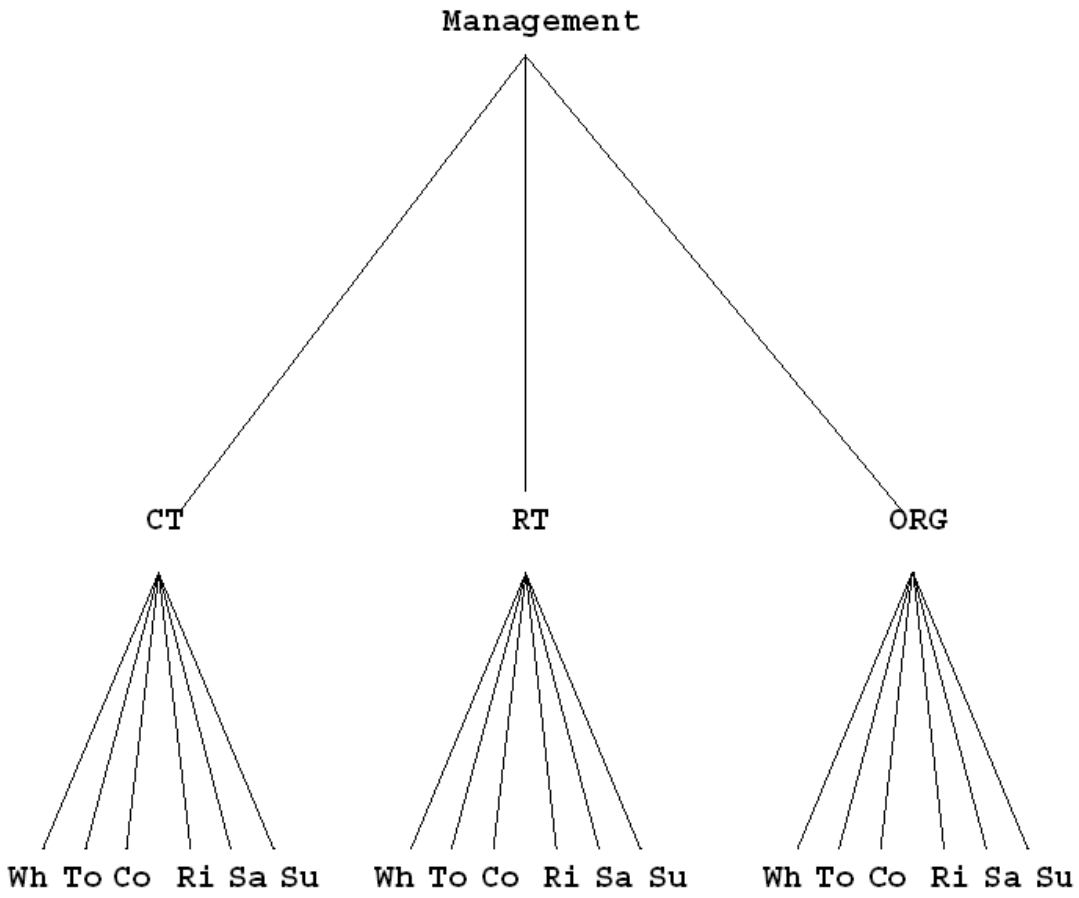


Figure 6.16. Yolo county crop and management alternative

Three different empirical factors were formulated to explain the decision:

- In Model I, the factors are experience in alternative management and yield potentials.
- In Model II, the factors are experience in alternative management, yield potential, and prices.
- In Model III, the factors are experience in alternative management and potential profits, measured as the product of the expected crop price and yield potential minus the total costs for each alternative estimated from the sample.

It is important to note that the productivity potential obtained from DAYCENT carries out the site-specific information on the following: Soil, topography, rainfall, microclimates, and other biophysical conditions of the field.

- Management practices applied to the field using information obtained from the Costs and Returns Studies elaborated by the Department of Agricultural and

Resource Economics of the University of California, Davis, for the region and each crop.

- Past land use history of the field for the previous nine years, which determines the current productivity of a particular land-use, and therefore the probability of choosing it.

The results indicate that the productivity of the field, based on complex biophysical conditions of the field, current and past, summarizes the multiple factors used by farmers to make decisions on what and how to grow in the field. In contrast, prices, which vary by crop and management, seem much less important as a determinant on the final decision. This result is reasonable, since it indicates that a farmer at the field level, knowing the properties of his land, is going to make use of it in the best biophysical way. It is very likely that prices have much more explanatory influence at the farm scale than at the field scale. This helps implement carbon sequestration payments, since it makes their success dependent to well-known biophysical conditions such as soil types.

The best way to summarize the results is through the elasticity of probability of adoption for the productivity potential in Models I and II, and for the profitability in Model III. The concept of elasticity gives us a measure of how much the farmer is going to respond to a change in the revenues a field can generate under different management alternatives. This piece of information is crucial to assess the success of a carbon sequestration program based on payments for crop and management adoption. The table below gives the elasticities, ε, for each crop and management in each of the empirical models, measured at the population means:

Table 6.9. Carbon payment

	Model 1			*Model 2*			*Model 3*		
	y^p			y^p			π^p		
	CT	*RT*	*Org*	*CT*	*RT*	*Org*	*CT*	*RT*	*Org*
ε_{Wh}	0.52	0.68	0.83	0.48	1.60	0.96	0.93	1.00	1.00
ε_{To}	0.42	0.85	0.91	0.30	1.23	0.98	0.60	0.86	0.75
ε_{Co}	-0.31	0.01	0.73	-0.47	2.60	0.97	0.88	1.00	1.00
ε_{Ri}	0.41	0.61	0.77	0.36	1.00	0.95	0.88	0.99	0.99
ε_{Sa}	0.70	0.81	0.86	0.69	1.32	0.97	0.93	1.00	1.00
ε_{Su}	0.57	0.81	0.87	0.56	1.27	0.97	0.74	0.99	0.99

y^p = productivity

π^p = profit

For all crops, regardless the empirical specification, the elasticity of alternative practices (reduced tillage and organic systems) adoption is positive and larger than those of conventional management. This makes a carbon sequestration program likely to succeed in fostering farmers' adoption of alternative practices with GHG mitigation. For instance, one could read that a 10% change in the productivity potential of a site for tomato increases the probability of using reduced tillage by 12.3% and organic systems by 9.8%. The probability of adopting conventional technology only changes by 3% for the same 10% change in productivity. Since this pattern repeats for all crops, one can conclude that farmers in Yolo County are more responsive when considering alternative management adoption than when considering conventional management. The elasticities show the expected positive signs with the only exception being for corn (although of the expected positive sign with respect to profits) for adopting conventional practices. This finding shows that adoption of conventional practices reduces with increments in yield probabilities available for a corn grower, but the probability of adopting is always augmented by the increase in y^p. In other words, corn will tend to respond particularly well to a carbon sequestration program particularly when accounting for this crop's effectiveness in carbon sequestration (cf. Section 4.3.).

6.5. From Individual Crop Supply Curves to an Aggregate Supply Curve

The previous sections showed the crop-management supply curves for the fields in this study's population (i.e., fields managed during the last four years by the same farmer).

This section will focus on obtaining an aggregate supply curve for each alternative management for Yolo County using the total population characteristics and the DAYCENT modeling of each field in the sample frame, that is, the study's population of fields. As indicated previously, the sample frame consists of the fields devoted to the six crops of interest in 2005 in which each area and use is specified, which were consistently managed by the same farmer for at least the last four years. Assuming that this model applies to the other fields in the county, namely the ones not managed by the same farmer in the last four years, the county acreage can be used to determine a county-level contribution to carbon sequestration.

The carbon sequestered for the whole region is computed as

$$CS_i(c) \times \frac{A(c)}{a_i(c)} \qquad \text{[Equation 15]}$$

where $CS_i(c)$ is the amount in Mg CO_2-eq of net sequestration for crop c in the field i, pertaining to the sample frame of area $a_i(c)$, and $A(c)$ is the total acreage in Yolo County devoted to cultivation of crop c in 2005.[18] The latter was obtained from the Pesticide Use Report.

Once the results are projected at the county level, each crop supply can be summed for a particular management. This operation calculates the amount of carbon that can be sequestered or avoided by adopting a specific management strategy in Yolo County and the associated cost of abatement. The cost of abatement, or "price" of carbon sequestration, is the break-even cost of adopting of that management (with respect to conventional practices). This price or cost per unit of Mg CO_2-eq does not includes farmers' preferences or perception of risks, since it has been statistically computed from the survey, and therefore, the following curves should be interpreted as abatement cost curves. One should expect a steeper curve if risk factors are included.

The results are shown in the Figure 6.17 and Figure 6.18.

6.5.1. Reduced-Tillage (RT)

For reduced till (RT), two aggregate curves were computed: one without fixed costs[19] and another which includes them.

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[18] This extrapolation could be refined by taking into account the soil type, using the DWR Land Use Survey for year 1997 in combination with SSURGO. However, the linearity assumption is probably reasonable at the aggregate level for a region such as Yolo County, where the dominant soil types are not so diverse. However, for larger scopes, for example, a California-wide perspective, soil types should be taken into account when aggregating.

[19] Machinery adoption was estimated from the survey as about $40/ha.

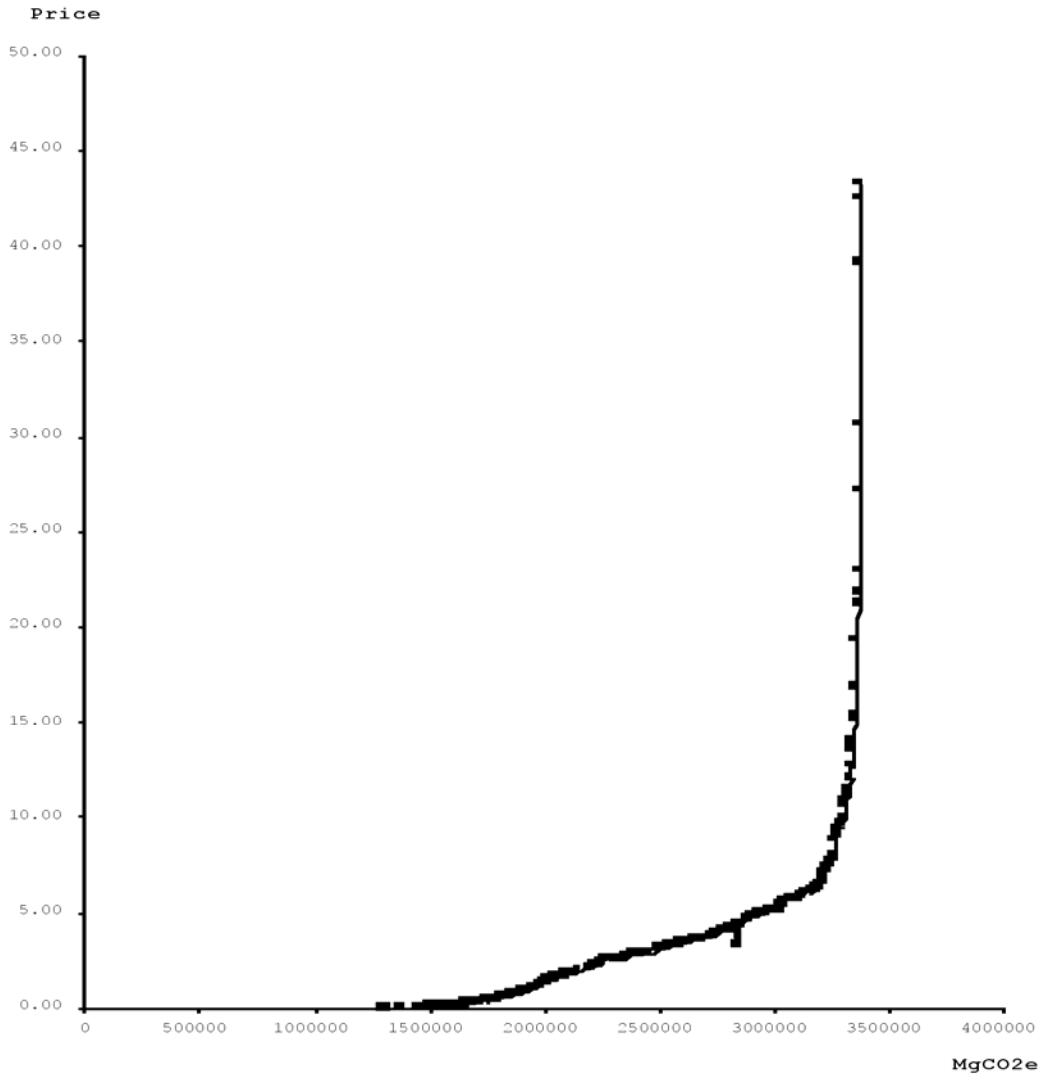

Figure 6.17. Yolo County aggregate carbon supply curve for RT

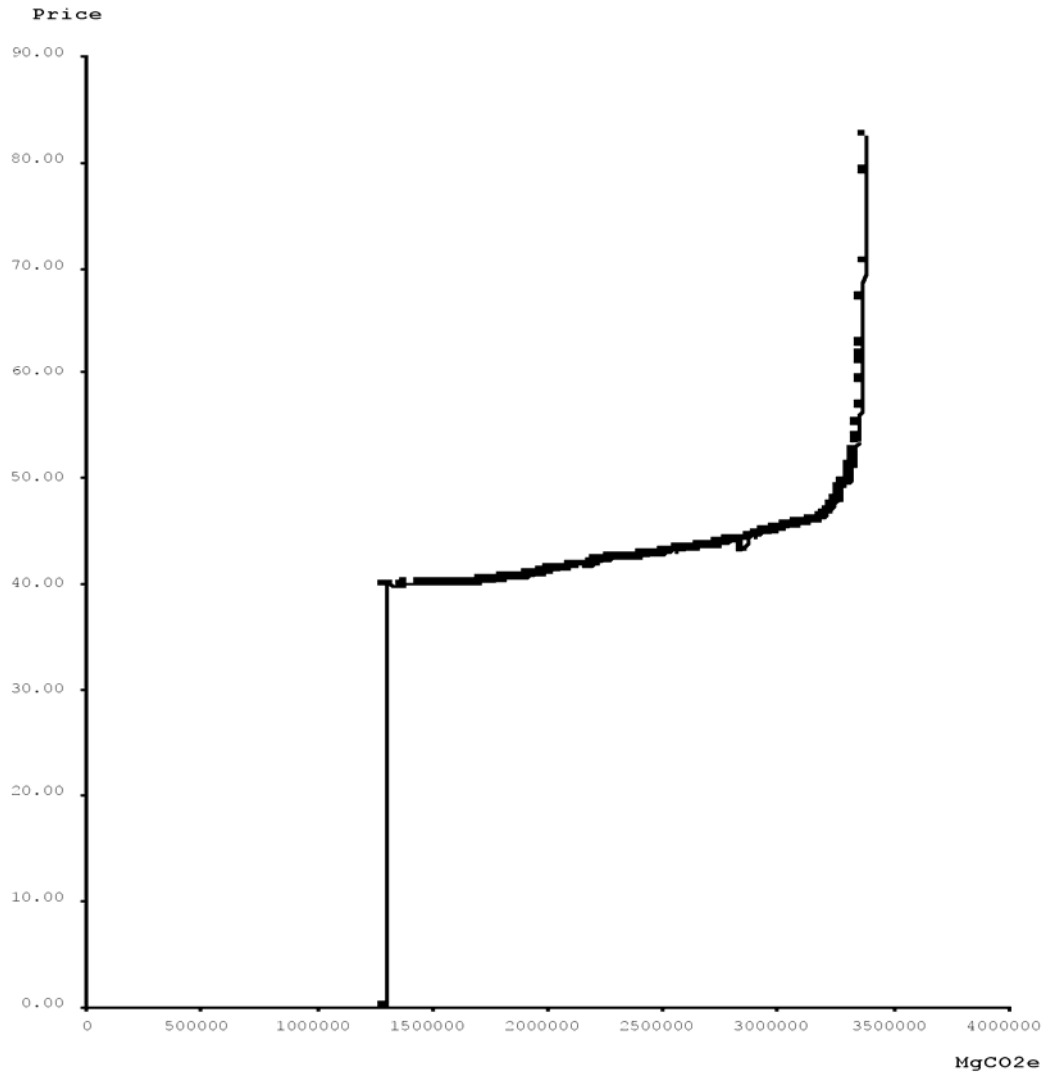

Figure 6.18. Yolo County aggregate carbon supply curve for RT (includes fixed costs)

It is important to model the contribution of each crop in the aggregation and how costly it is to adopt RT for each crop. The pie chart in Figure 6.19 shows the allocation of the total Mg CO_2-eq among crops and the histogram of break-even prices for each of them.

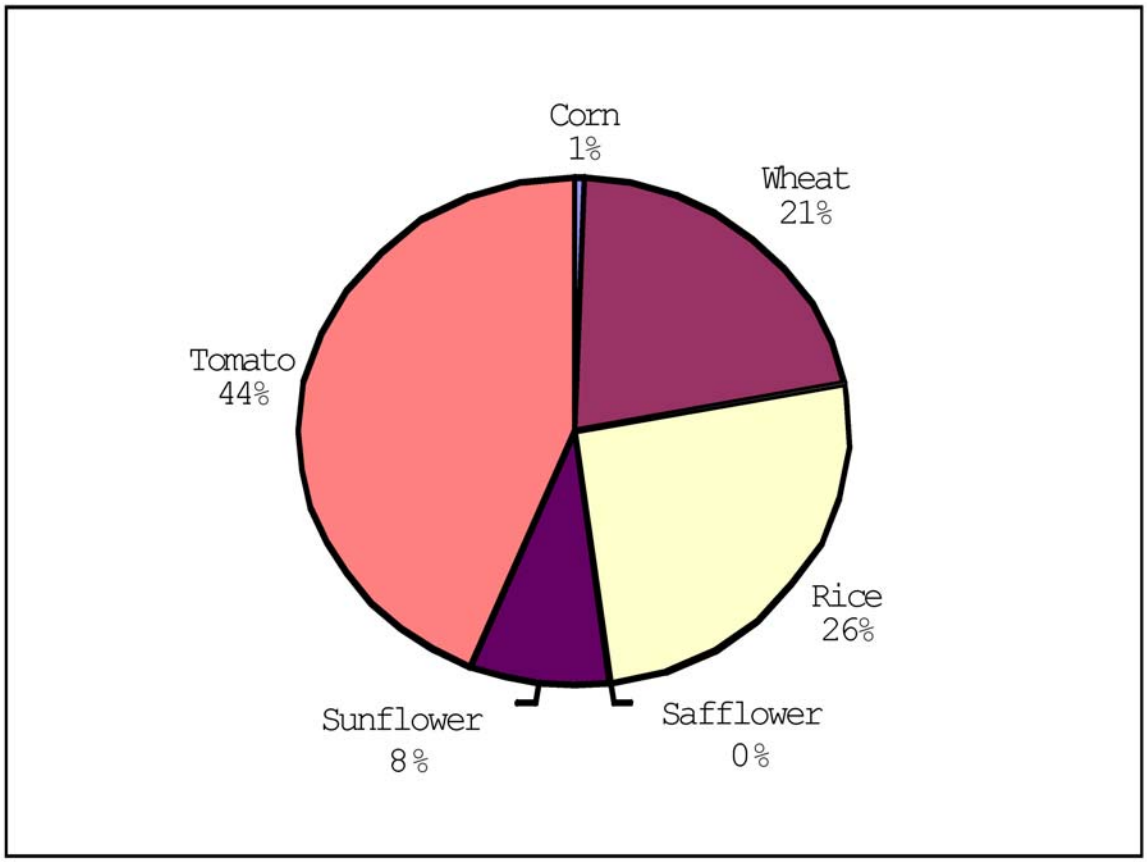

Figure 6.19. Allocation of total RT cost per crop

Figure 6.19 shows that tomato is the highest contributor to GHG reduction. This is true because it is the most important crop in Yolo County and because of the agronomic processes involved in tomato cultivation under RT. This pattern repeats for all alternative managements. Corn and safflower hardly contribute at all to the aggregate sequestration under RT.

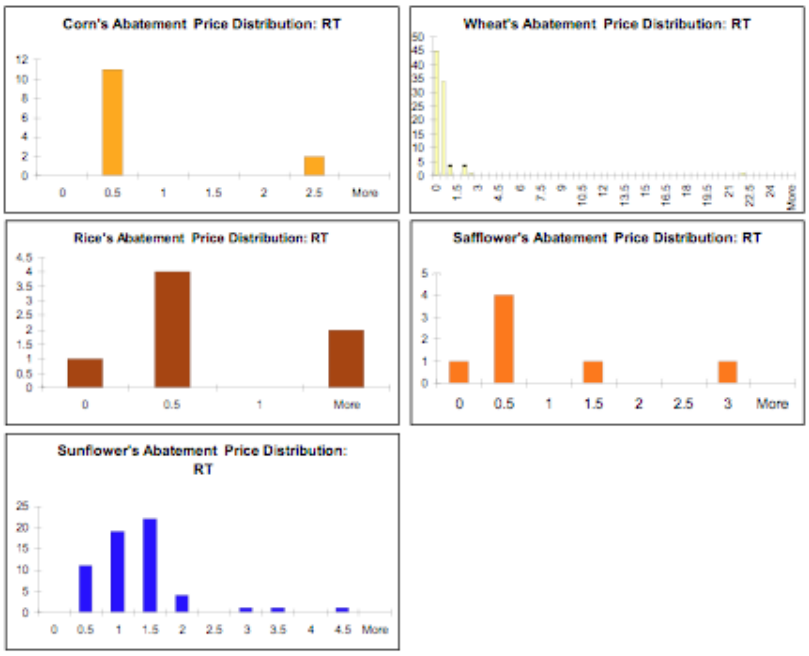

Figure 6.20. Tomato's abatement price distribution

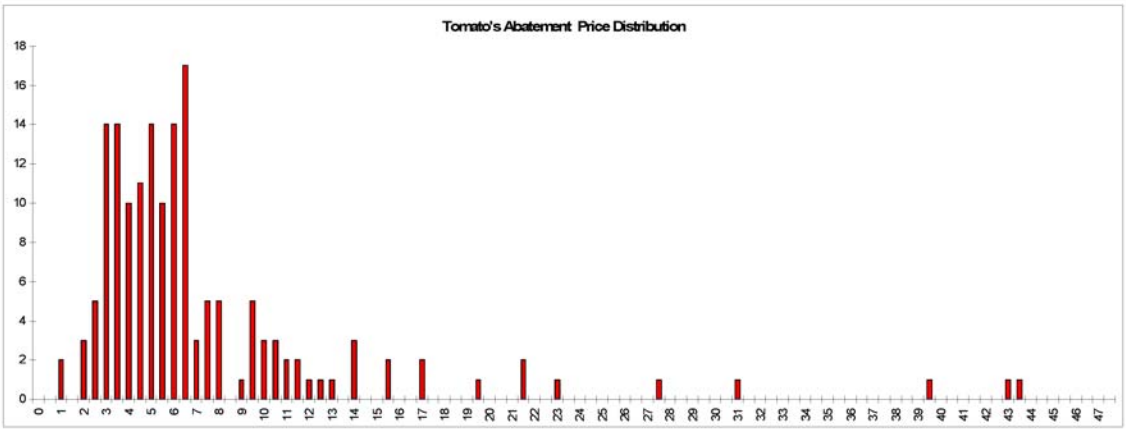

Figure 6.21. Tomato's abatement price distribution

The above distributions are based on the variable costs of adoption. This assumption implies that once the investment has been made to adapt machinery for RT, this management practice is inexpensive in corn, wheat, rice, safflower, and sunflower production. Tomato is more expensive, although the distribution shows that it is very skewed to the left in terms of prices.

6.5.2. Organic Systems

There are several combinations of Organic Systems that have been already adopted in Yolo County: reduced-till with manure (RT+MA), conventional tillage with manure

(CT+MA), and conventional tillage with manure and cover cropping (CT+CC+MA). Figure 6.22, Figure 6.23, Figure 6.26, and Figure 6.29 offer aggregate supply curves for each of these systems in Yolo County.

Reduced Tillage and Manure Application (RT+MA)

Figure 6.22 and Figure 6.23 show the aggregate supply for Yolo County under RT+MA management, with and without fixed costs.

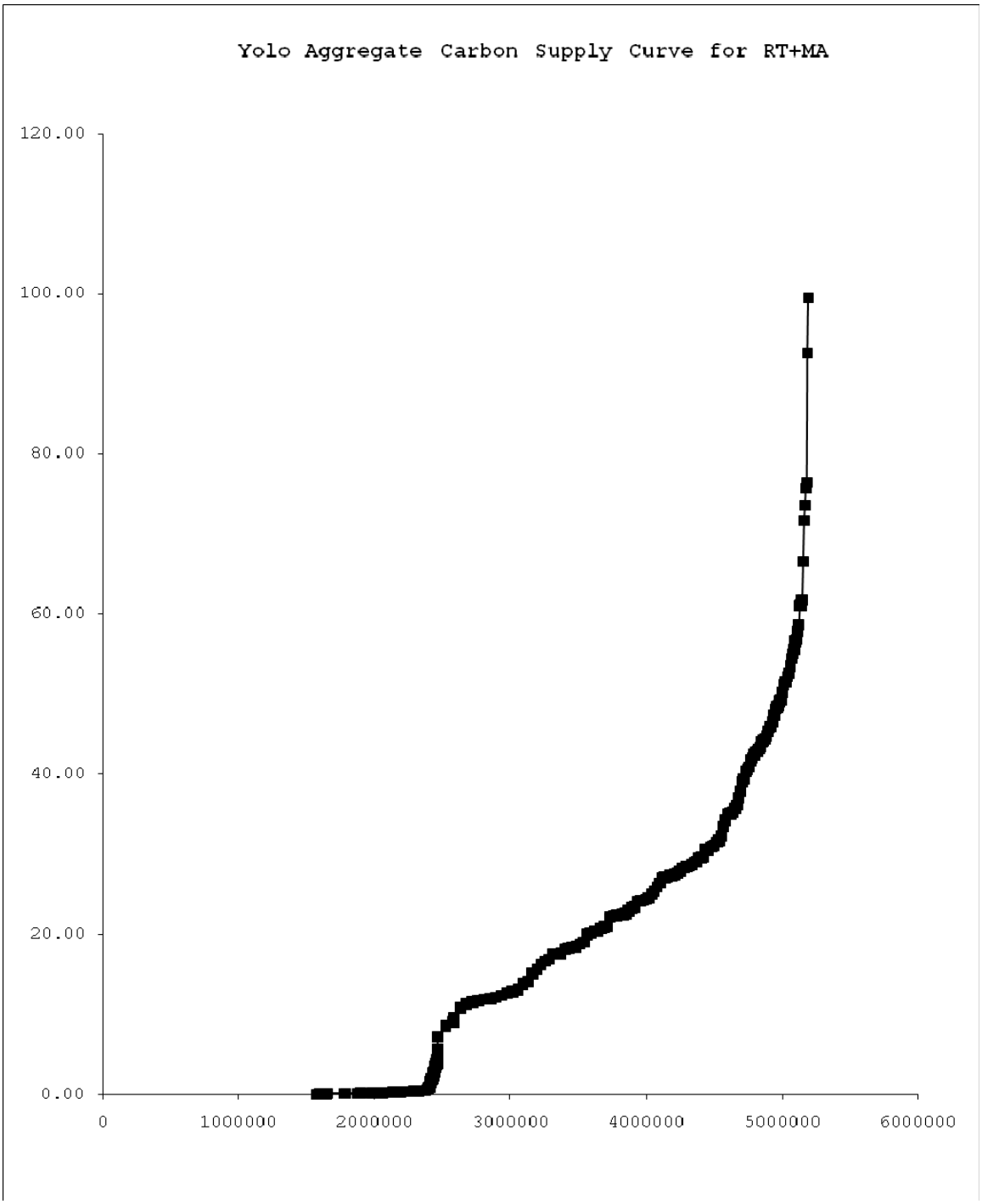

Figure 6.22. Yolo County aggregate carbon supply curve for RT+MA

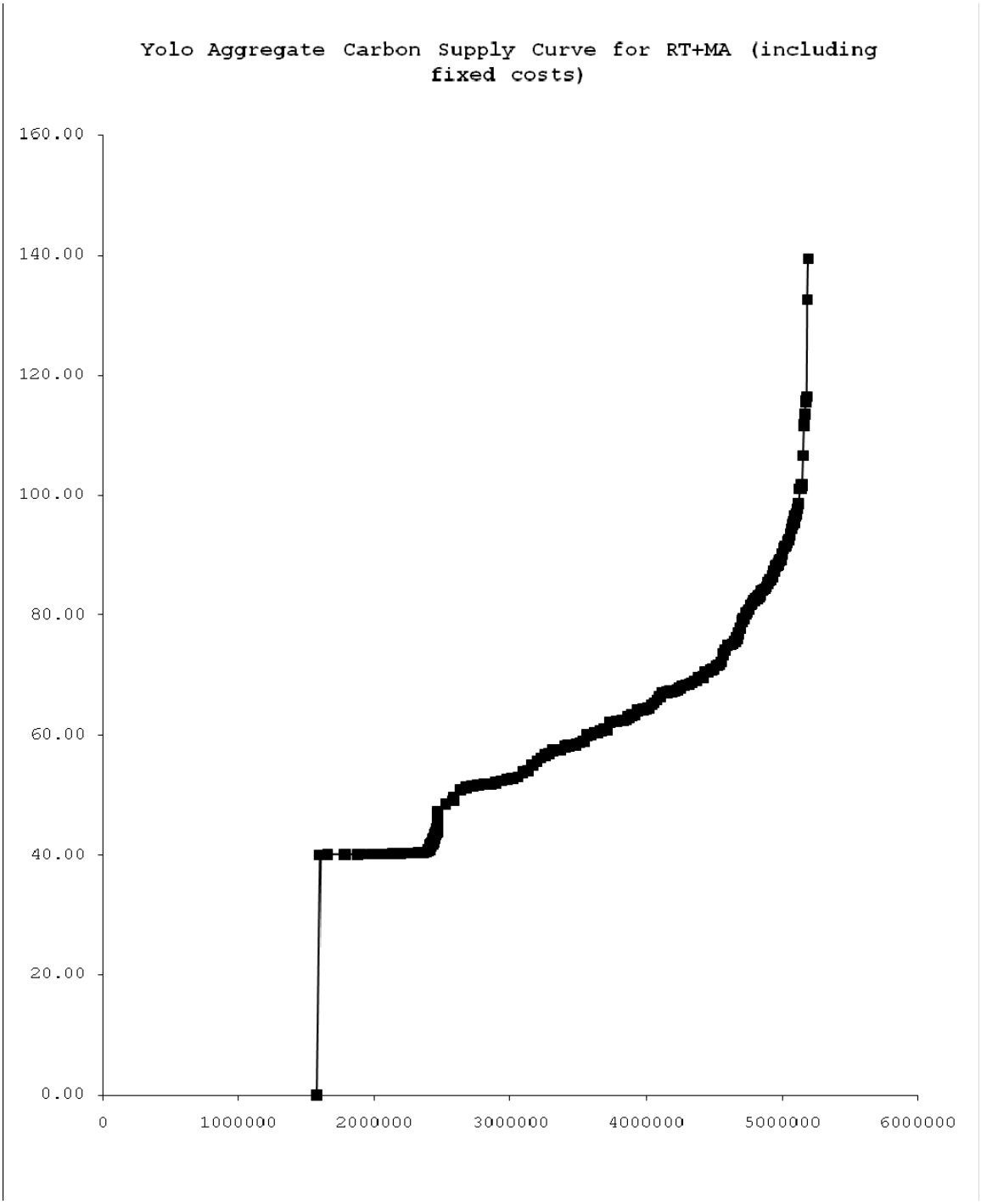

Figure 6.23. Yolo county aggregate carbon supply curve for RT+ MA (including fixed costs)

The results of the allocation of the net CO_2-eq sequestered under RT+MA are very similar to those of RT, as shown in Figure 6.24.

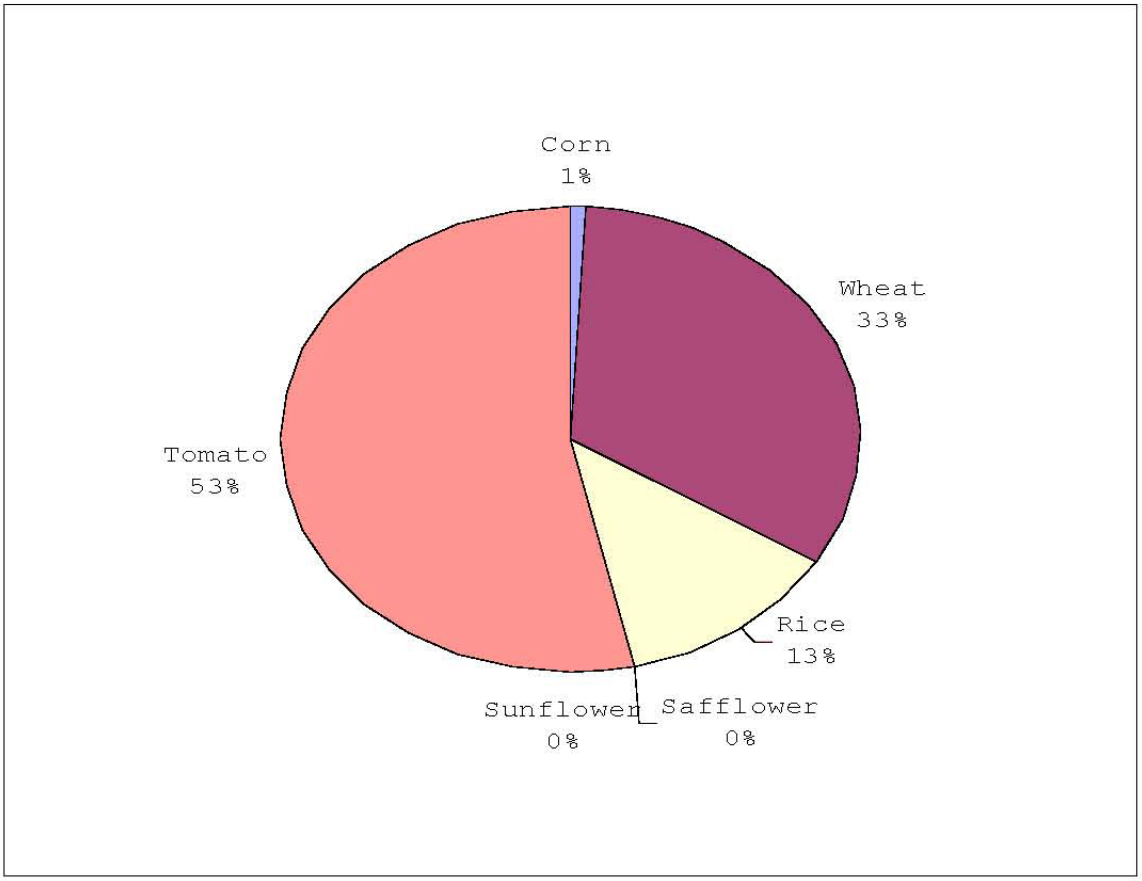

Figure 6.24. Crop contribution to sequestration (RT+MA)

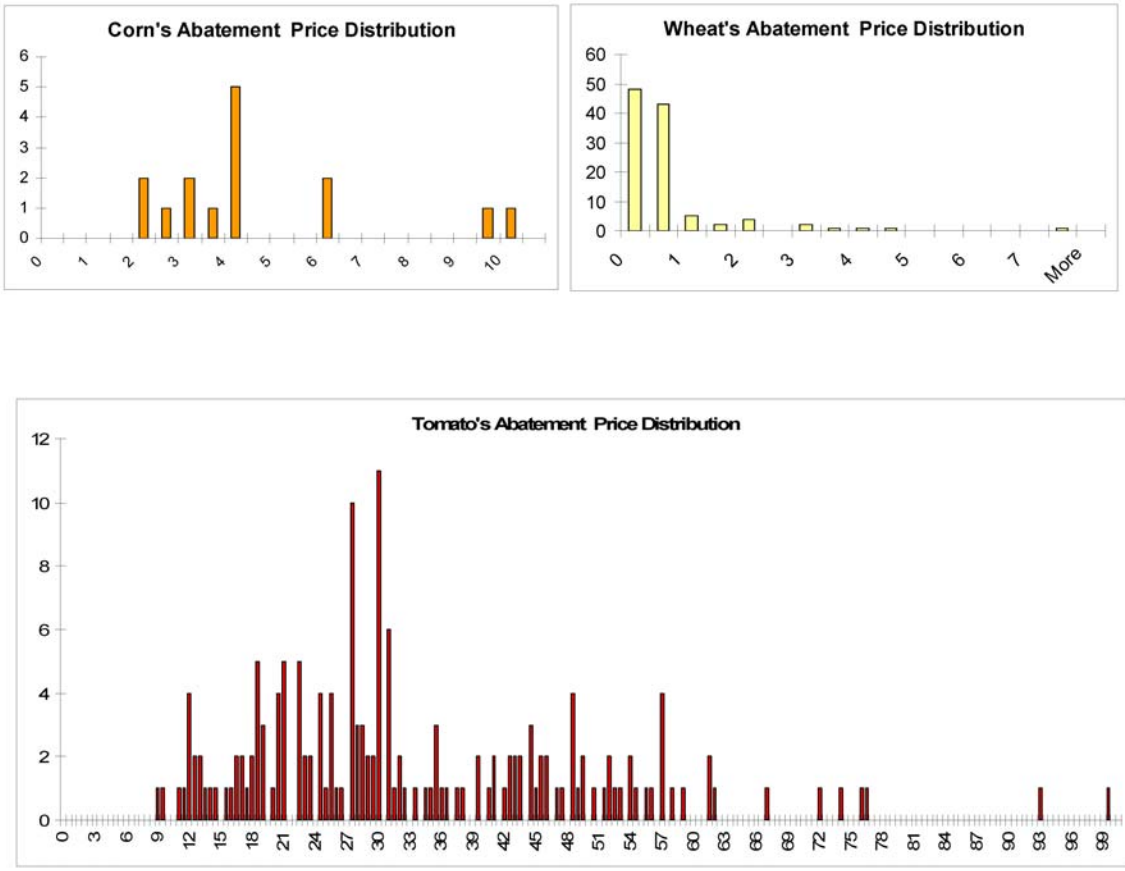

Figure 6.25. Distribution of crop response by price to RT+MA

Conservation Tillage and Manure Application (CT+MA)

Price of abatement under CT+MA is much higher than RT+MA, especially for tomatoes, which is the main to offset GHGs under this management.

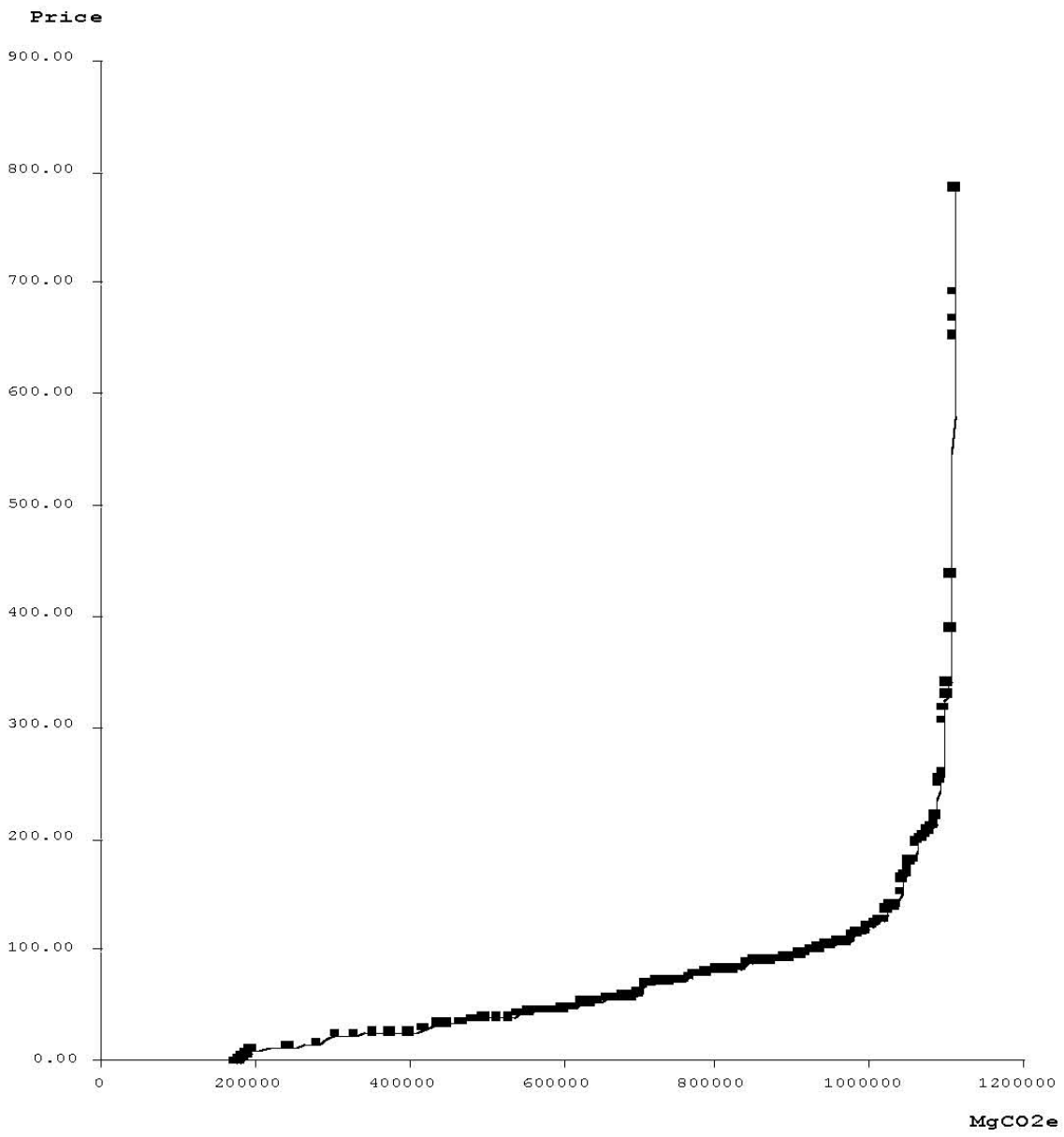

Figure 6.26. Yolo County aggregate carbon supply curve for CT+MA

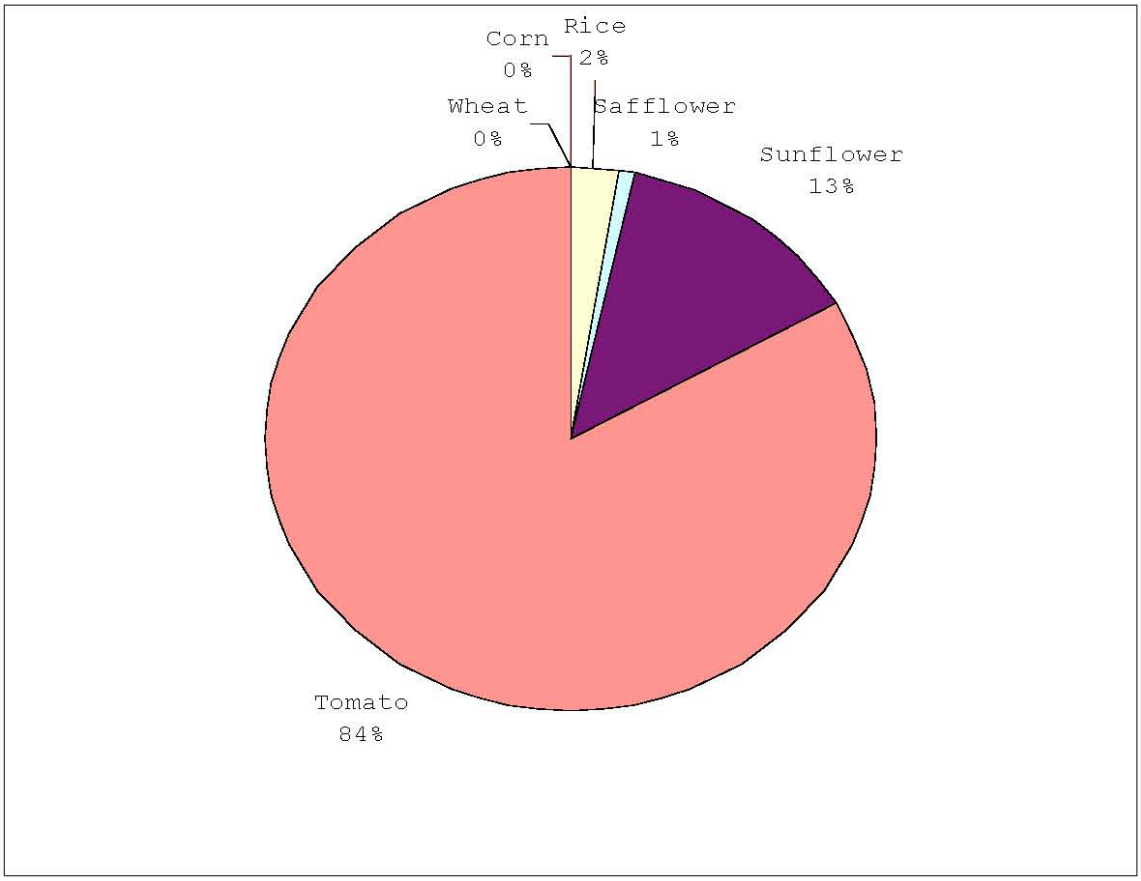

Figure 6.27. Crop contribution to sequestration under CT+MA

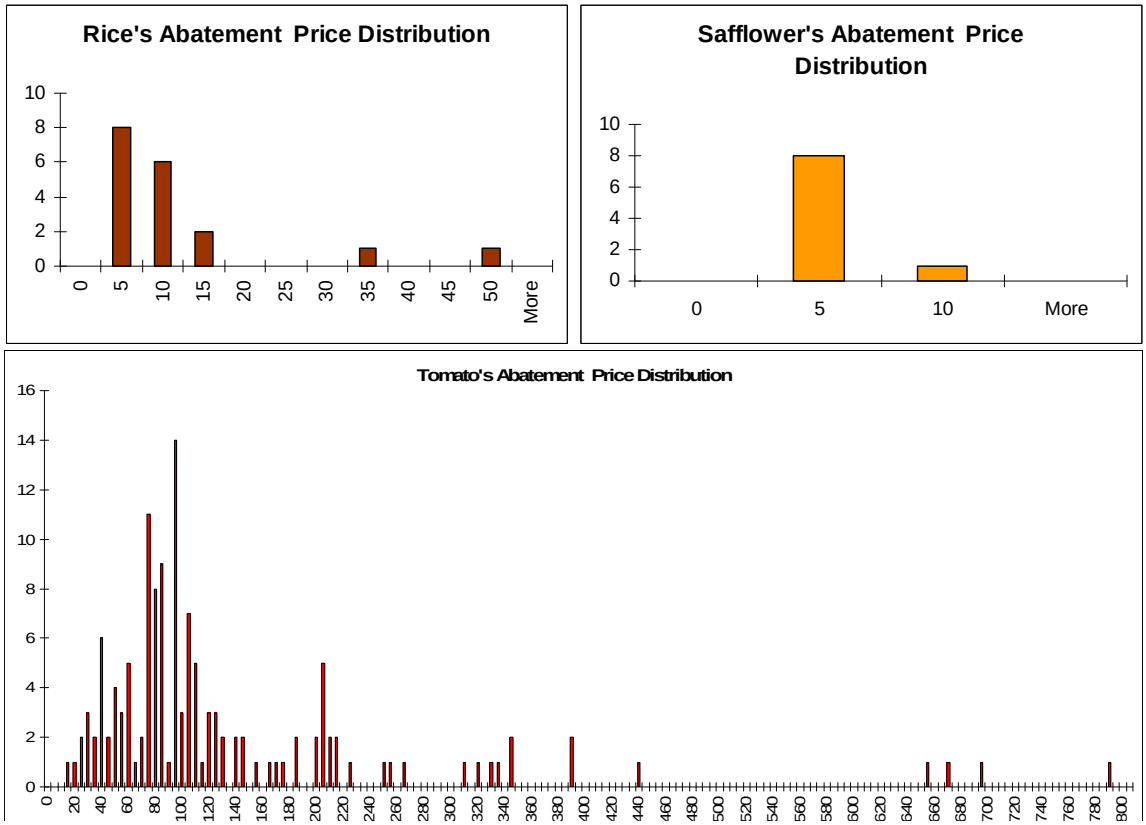

Figure 6.28. Distribution of crop response by price to CT+MA

Conservation Tillage, Cover Cropping, and Manure Application (CT+CC+MA)

In this case, the use of CC in combination with MA reveals itself as a cost-effective way of mitigating. When one compares it against CT+MA, the aggregate supply becomes similar to the RT (in terms of prices)

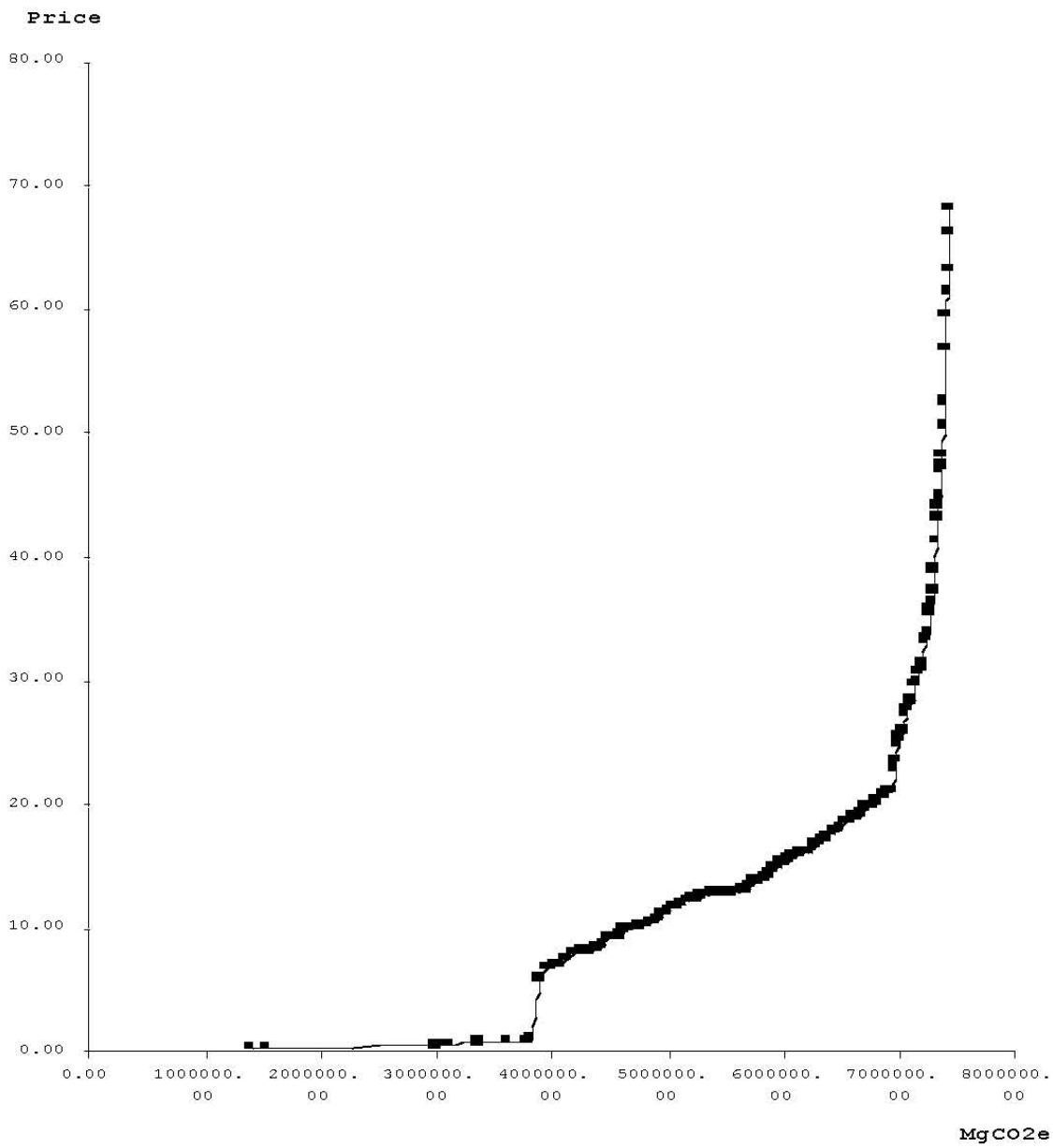

Figure 6.29. Yolo County aggregate carbon supply curve for CT+CC+MA

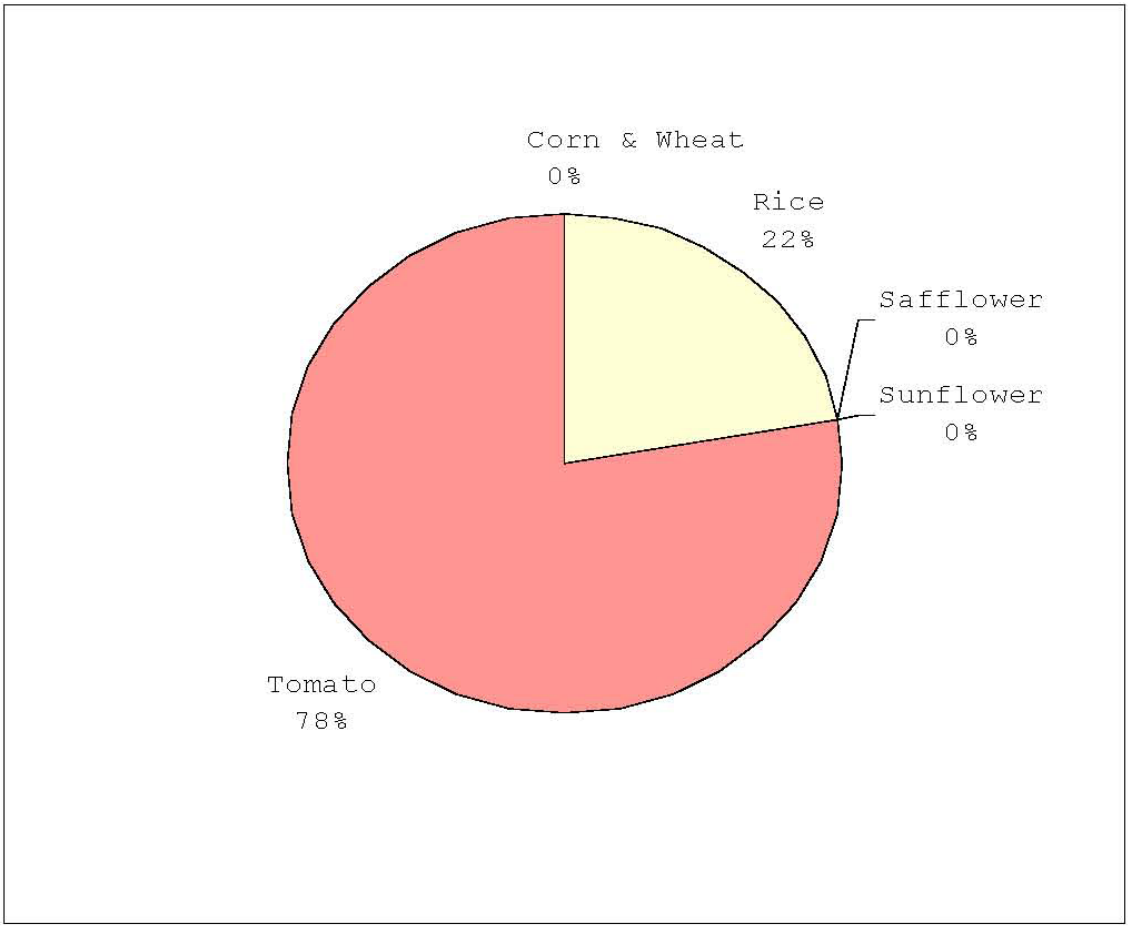

Figure 6.30. Crop contribution to sequestration under CT+CC+MA

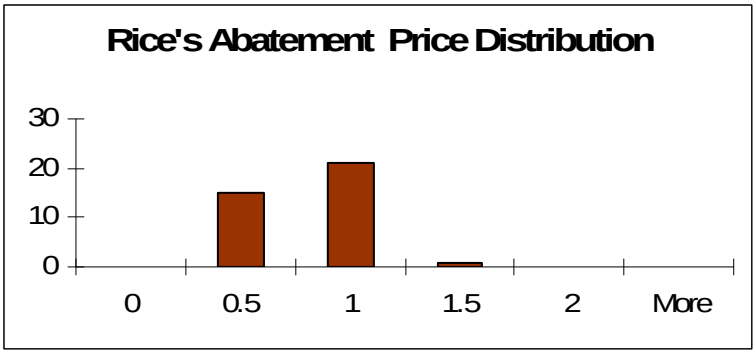

Figure 6.31. Distribution of crop response by price CT+CC+MA

6.6. Conclusions

The most practical management option in terms of the ease of monitoring and probability of adoption in Yolo County is reduced tillage (RT). The regional model can be used to simulate the number of farmers who are adopting reduced tillage on different crops under a range of prices. The DAYCENT model can be used to link a quantity of carbon sequestered to the crop and acres, thus enabling us to generate the county-level supply function that shows the relationship between carbon payments and tons of carbon sequestered by agriculture in Yolo County. Figure 6.32 shows this.

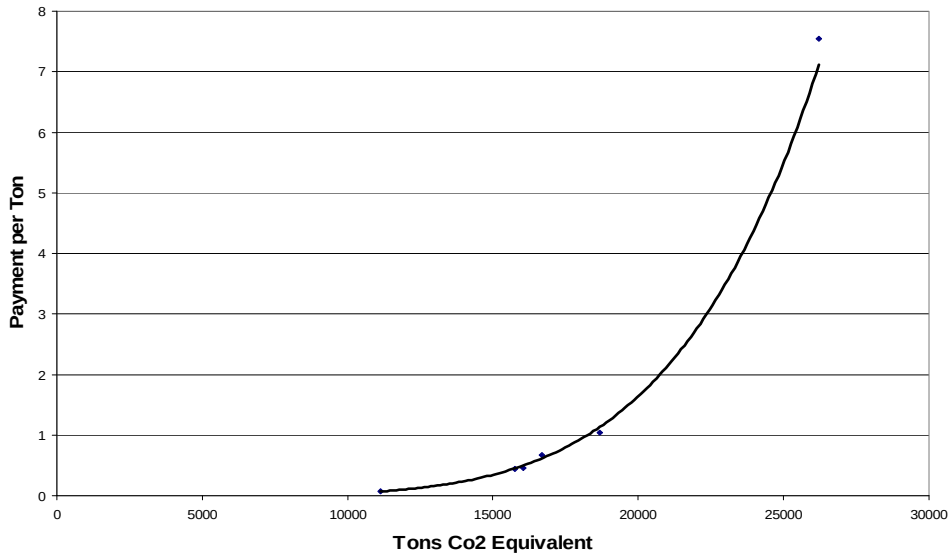

Figure 6.32. County-level reduced tillage sequestration – Yolo County

Some conclusions can be drawn from the supply function in Figure 6.32. First, agronomic and economic models can be combined to develop regional carbon sequestration supply functions from agriculture. Second, farmers will change their crop technologies in response to sequestration payments. Third, the cost of sequestration changes with soil and crop type. These supply functions in Figure 6.32 shows that Yolo County can sequester 33,000—39,000 tons of carbon by adopting reduced tillage practices in response to payments of $3–$8 per ton per year. This level of carbon sequestration is approximately 3% of the total county carbon release. In addition, if cover cropping with rice could be feasibly adopted, the total sequestration quantity by agriculture could be doubled. It should be noted that the shape of a supply function indicates that relatively low carbon payments can induce sequestering technologies to be adopted by farmers.

7.0 Glossary

AB 32	Assembly Bill 32, Global Warming Solutions Act of 2006
AG	aboveground
AgRIC	Agronomy Research and Information Center
ARB	California Air Resources Board
CC	cover cropping
CCAR	California Climate Action Registry
CCOF	California Certified Organic Farmers
CCT	conventional corn-tomato rotation
CERES	California Environmental Resources Evaluation System
CH_4	methane
CIMIS	California Irrigation Management Information System
CO_2	carbon dioxide
CO_2-eq	carbon dioxide equivalents
CRP	Conservation Reserve Program
CSA	Conservation Security Act
CSP	Conservation Security Program
CT	conventional tillage
DNDC	DeNitrification-DeComposition model
DPR	Department of Pesticide Regulation
DWR	Department of Water Resources
EPIC	USDA ecosystem model
GHG	greenhouse gas
GIS	geographic information system
Gt	gigaton (10^{15} g)
GWP	global warming potential
LCT	legume cover crop, corn-tomato rotation
LTRAS	Long-Term Research on Agricultural Systems

MA	manure application
Mg	megagram (10^6 g)
Mg CO_2-eq	megagram carbon dioxide equivalent
MSD	mean square deviation
NASS	USDA National Agricultural Statistics Service
NH_4	ammonium
NO	nitric oxide
NO_3^-	nitrate
N_2O	nitrous oxide
NPV	Net Present Value
NRCS	Natural Resources Conservation Service
O_2	oxygen
OCT	organic corn-tomato rotation
PSU	primary sample units
PUR	pesticide use reports
RT	reduced tillage
SAFS	Sustainable Agriculture Farming Systems
SOC	soil organic carbon
SOM	soil organic matter
SSU	secondary sample units
SSURGO	Soil Survey Geographic Database
Tg	teragram (10^{12} g)
TRS	township range section
USDA	United States Department of Agriculture
U.S. DOE	United States Department of Energy
WESTCARB	West Coast Regional Carbon Sequestration Partnership
WFPS	water filled pore space
WSREC	University of California West Side Research and Extension Center

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Appendix A

Cropping Systems in California

A.1 California Agricultural History

The relative size of the SOM pools used by DAYCENT cannot be experimentally measured. Therefore, historical runs are employed to model the size of these pools.

Although Californian agriculture was pioneered around 1850, cropping at a larger scale only started from 1870. Therefore, this discussion will divide the history of Californian agriculture roughly into three periods: (1) native grassland between 0 and 1869, (2) emergence of agriculture between 1870 and 1949, (3) transition to modern agriculture between 1950 and 1969. Current-day practices will be described in the next section.

A.1.1 Pre-agricultural Period (pre 1870)

In the pre-agricultural period, California was dominated by native perennial grasslands. In Yolo County, these consisted mainly of C3 grasses, with a growing season extending from November until April, when rainfall exceeds potential evapotranspiration. Along river systems such as the Sacramento River, some marshlands developed. About one third of the area of Yolo County was covered with rank-growing reeds and grasses. Native Americans used controlled burning to encourage new plant growth. Overgrazing and drought made it impossible for the native grasslands to survive. Today, the lowland areas in California are dominated by non-native annual grasses from the Mediterranean area (Potthoff et al. 2005). These grasses have a typical seasonal change in aboveground biomass. They grow rapidly after the first rainfall. Their growth slows during winter but increases again in spring. The grasses finally die and set seed (Bortolome and McClaran 1992). Areas without growth are very common in these annual grasslands and limit the productivity (Fehmi et al. 2001). For these annual grasses, most root biomass is located in the top of the soil profile, while it is more evenly distributed over the whole profile in perennial grasslands. An overview of some characteristics of these grasslands is given in Table A.1.

Table A.1. Characteristics of native grasslands in California. Values are averages ± standard error.

Characteristic	Value	Site	Ecosystem	Reference
shoot:root ratio	1.75	Jasper Ridge		Valentini et al. (1995)
annual production	100–200 g dry matter m^{-2}	Jasper Ridge		Valentini et al. (1995)
annual production	272–285 ± 29 g dry matter m^{-2}	Hopland Field Station, (Mendocino County)		Bartolome and McClaran (1992)
root biomass	200 g DM m^{-2}	Hastings Reserve (Carmel Valley)	annual and perennial	Potthoff et al. 2005
relative root distribution in the top 20 cm	53%	Hastings Reserve (Carmel Valley)	perennial	Potthoff et al. 2005
relative root distribution in the top 20 cm	67%	Hastings Reserve (Carmel Valley)	annual	Potthoff et al. 2005

A.1.2 Emergence of Agriculture (1870–1950)

By 1870, most of the arable land in Yolo was purchased, preempted, or homesteaded. In this initial period, mostly small grains (mainly wheat and barley) were grown in the winter season. Horses and mules were used to pull the gangplows. After harvest, cattle would usually graze the freshly cut grain stubble. During the 1890s, crops diversified. Some fruit orchards and vines were planted in the late nineteenth century. Later, also nut orchards were planted, especially in southwestern Yolo. Between 1900 and 1920 the land along the Sacramento River was reclaimed and could be irrigated with the water from the river. Irrigation and the availability of water led to the cultivation of alfalfa (for hay), rice, and sugar beets during the summer. By 1930, electric power could power the pumps to irrigate the rest of the county, which further diversified crops to include corn and tomatoes.

A.1.3 Transition to Modern Agriculture (1950–1969)

From 1950, tomato harvesting was mechanized, with a steady increase in area (Figure A.1). In addition, inorganic fertilizer was available. Its use increased from 1950 until 2000 (Figure A.2). Crops such as safflower were introduced (Figure A.1).

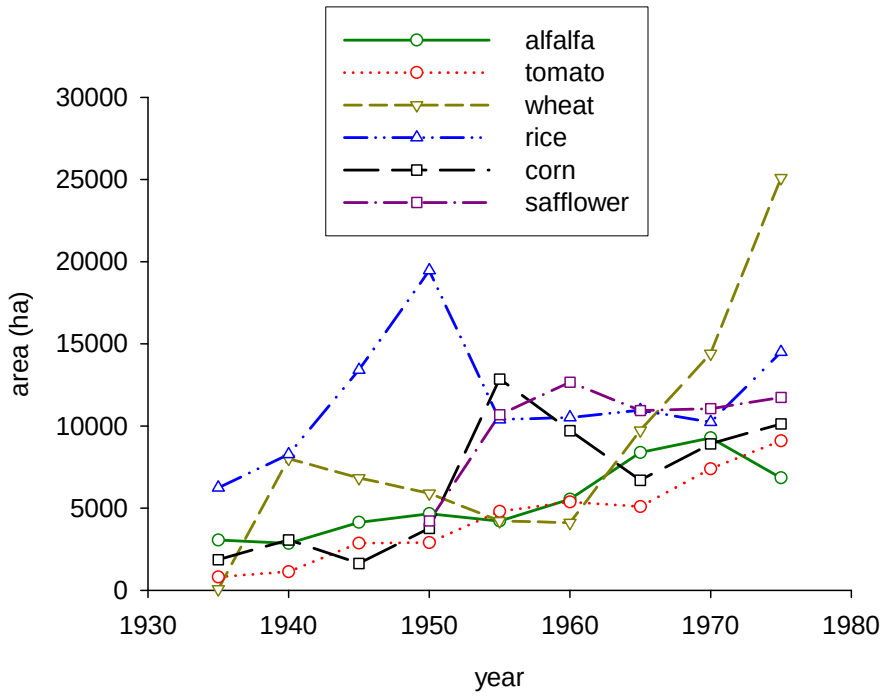

Figure A.1. Historical acreage data (1940–1975) from the agricultural commissioner yearbooks for different crops. Values are averages over five years.

Source: Agricultural Commissioners yearbooks from 1930 to 1980, and NASS 2007

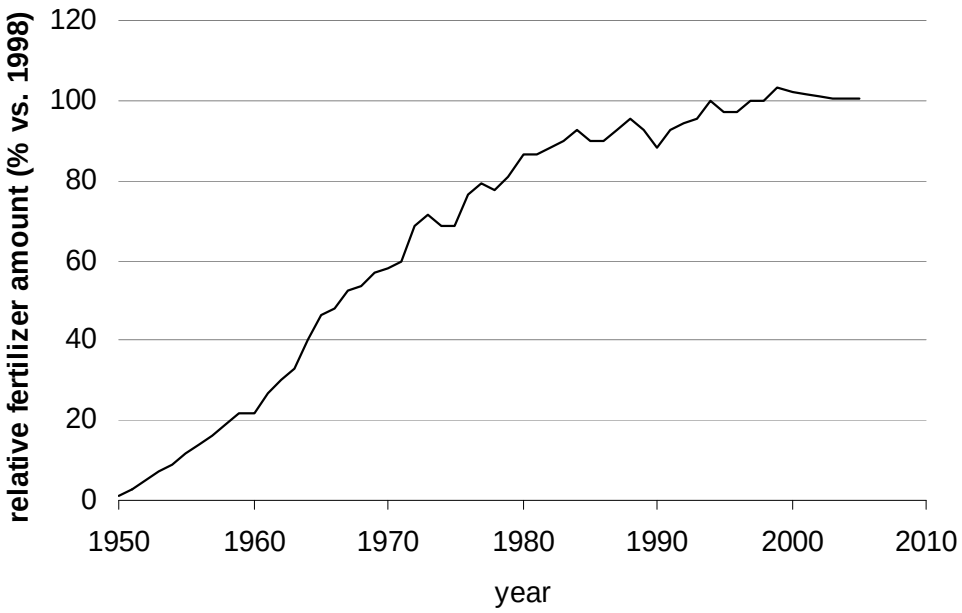

Figure A.2. Historical increase in fertilizer amounts from 1950–2005. Values are expressed as percentage vs. 1998.

Source: NASS 2005

A.2. Cropping Systems

To calibrate a biogeochemical model, extensive information on crop management specific for the area studied is necessary. This includes a day-by-day account of all of the operations performed by the farmer.

A.2.1 Alfalfa

Alfalfa is a high-protein perennial hay crop. It is grown on deep, well-drained, medium-textured soils such as a sandy loam to a clay loam. Water logging (even infrequent or non-permanent) on heavier (silty clay to clay) soils will prevent optimal crop growth conditions. Soil pH should be neutral (Orloff and Carlson 1997) and free of salt or alkali problems.

In the Central Valley, alfalfa is planted preferentially before October 15 if the crop rotation permits this (UCCE 2007). If this is not possible, early February is the second best window for planting

Above 37°C, plant growth will slow down (Hanson et al. 1988). Alfalfa is typically grown for four consecutive growing seasons. After the fourth season, the roots die and the crop needs to be replanted. There are multiple cuttings a year, depending on the local climate. In Yolo County there are on average 6–7 cuttings per season (a minimum of five and a maximum of eight) (Figure A.3). The first cutting is typically around mid-April. From then, the hay is cut every 28 days, until the end of October. No irrigation is required before the first cutting; irrigation is usually done 10–12 days after the first cutting (it takes 5–7 days to dry and bale the crop), and is stopped 8–10 days before the next cutting. In Yolo County, the average total yield is 7.4 t ha^{-1} and the maximal yield is 15 t ha^{-1} (values are reported on a standardized moisture content of 10%). In Fresno County there are 8 cuttings per season, in the Imperial Valley there are up to 11 cuttings per season. Alfalfa is a nitrogen-fixing crop. Therefore, no additional N fertilizer is required.

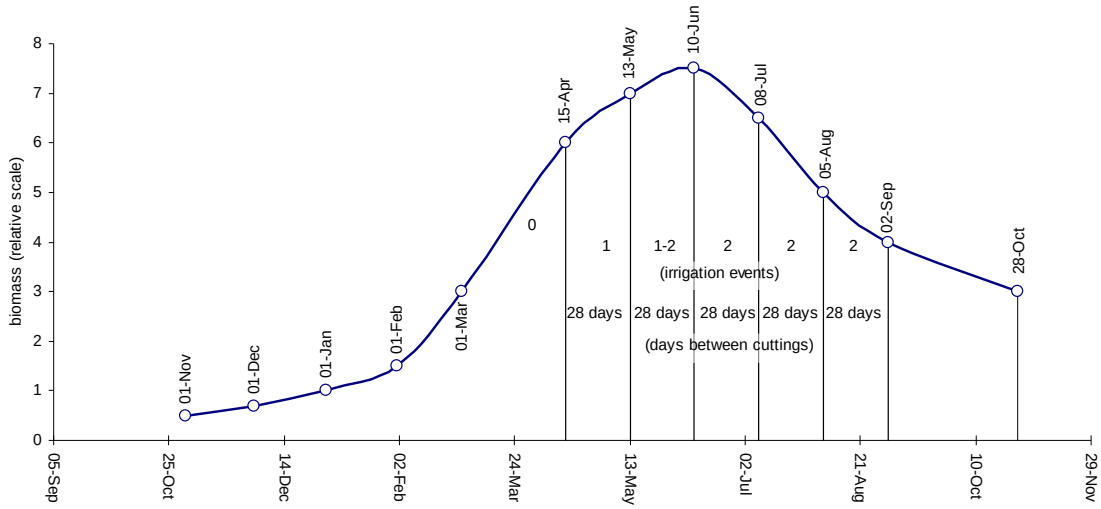

Figure A.3. Typical cutting (vertical bars) and irrigation schedule for alfalfa in Yolo County
Source: UCCE 2007

A.2.2. Corn

In Yolo County, corn is usually grown for grain. Corn requires a well-drained, silty loam or loamy soil with high moisture-holding capacity, a high amount of organic matter and a pH between 5.3 and 7.3. Planting occurs generally about two weeks after the average date of the last killing frost. In Yolo and Sacramento counties, this is around mid March through April (AGRIC 2007). At this time, there should still be sufficient rainfall and the soil temperature should be high enough (min 13˚C). The seed bed is usually prepared in the fall for an early planting (March) or early in the spring for an April planting. For late plantings, the risk of adverse temperatures and low humidity during pollination increases. A pre-plant irrigation might be necessary as corn should be planted into a moist seedbed. An optimal germination can be expected with temperatures between 27˚C and 32˚C. In California, most corn is furrow irrigated. Typically, total water application ranges from 90 to 106 centimeters (cm) of water, which is applied in 5 to 9 irrigations. The first irrigation is applied approximately 30 to 40 days after planting, unless sufficient rainfall has occurred to moisten the area at least to seed depth. Corn is sensitive to moisture stress. The most critical stages are the establishment of the secondary root system and the tasseling-to-silking stage (initiation of the formation of grain). During the vegetative and the pollination period, eight weekly irrigations are the best option. The grain filling period should be started with a full moisture profile and most fields will need an extra irrigation during this period. At maturity (130 to 175 days after planting, depending on the variety), the crop has to reach a moisture content of about 35%. Recently, most growers have not harvested until the moisture content has reached 15.5% or lower, in order to avoid drying costs. The U.S. standard for grade 1 corn requires a grain moisture content of less than 14%.

Corn planted early in spring needs about 225 kg N ha^{-1}. A general range would be from 170 to 300 kg N ha^{-1} (Figure A.4). A common practice is to apply this fertilizer as a starter fertilizer at planting and then as a side dress. The starter fertilizer should contain about 4.5 to 6.8 kg of nitrogen and some phosphorus. Many growers choose not to apply fertilizer pre-plant because this might dry out the seedbed (AGRIC 2007). Corn needs only 2% of its nitrogen during the first month. Most of the nitrogen is absorbed 6 to 12 weeks after planting. Nitrogen side-dressing is applied before the corn is 30 cm tall. The safest source of nitrogen for side-dressing is UN32 solution. Phosphorus is usually applied in a starter fertilizer at 10 to 30 kg P ha^{-1}.

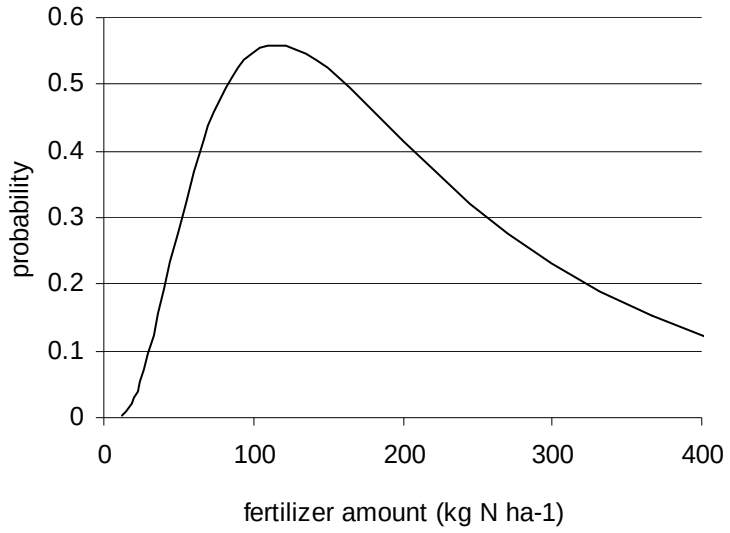

Figure A.4. Probability density function for the fertilizer amount used for corn

Source: ERS 1995

A.2.3 Cotton

Cotton is an annual crop usually grown under contract. Warm springs, hot summers, dry falls and wet winters are optimal for cotton. The crop can be planted on almost every soil, but a fertile, well-drained soil with a good water holding capacity gives the best result. Cotton is planted between the beginning of March and the first of May. During the growing process, cotton crops need warm days and cool nights. The plant is in all stages of the development very sensitive to temperature. The optimal day temperature is around 28˚C and the highest temperature a plant can survive is around 32˚C (Reddy et al. 1999). Most of the time furrow irrigation is used. A cotton plant needs about 200 kg N ha^{-1} during the entire growing season. After 180 to 200 days (usually sometime in August) the crop will reach full maturity. At that time, irrigation is stopped and the plant dries. Harvest is initiated when the plant is dry enough (a moisture content of 12% or lower). About 37.3% of the seed boll is cotton lint (Mondino et al. 2004). The *harvest index* is defined as seed boll weight divided by total aboveground weight. Reported yields are usually lint yield, and not the total cotton seed yield, which is harvested. About 75 kg N ha^{-1} is provided according to the ERS (1995) (Figure A.5). Around 185 kg N ha^{-1} is provided according to the cost and return studies of the department of Agricultural and Resource Economics at UC Davis (ARE 2007).

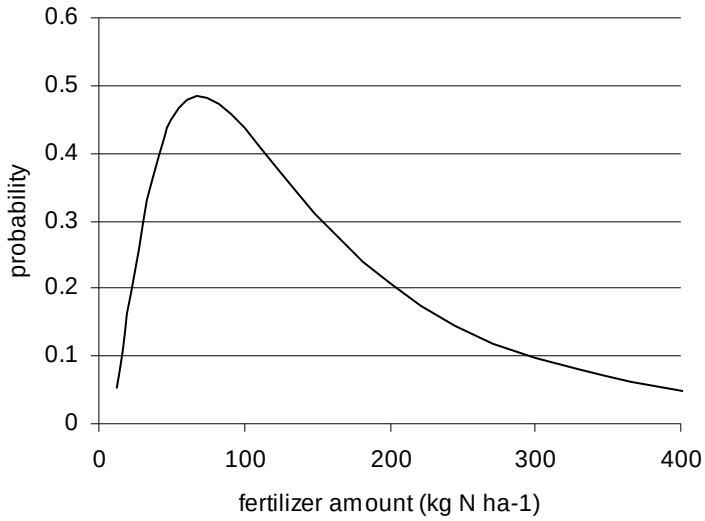

Figure A.5. Probability density function for the fertilizer amount used for cotton

Source: ERS 1995

A.2.4. Rice

Rice in California is grown primarily in continuously flooded, flow-through systems. Rice is grown on fine-textured soils with clay contents of 25%–70% (clays, silty clays, and silty clay loams), which are poorly drained and have an impervious hardpan (UCCE 1997). If fields are flooded during winter, they are usually drained by late February or early March to allow adequate soil drying for seedbed preparation. When the soil is sufficiently dry, fields are lightly disked prior to deeper cultivation such as disking or plowing. In April, some additional soil management for weed control is done, and a pre-plant fertilizer is added. An average starter N application of 30 kg N ha^{-1} is done, which can range from 6 to 64 kg N ha^{-1}. The fertilizer is incorporated or injected to a depth of 5 to 10 cm before flooding. Late-maturing varieties are sown by the end of April; early-maturing varieties can be sown later. Seeding onto fields occurs mainly by airplane on a flooded field (UCCE 1997). Season length ranges from 130 to 175 days. A temperature between 20˚C and 31˚C is necessary in the vegetative stage. The optimal temperature in the reproductive and maturity stages is located between 21˚C and 35˚C (Sass and Cicerone 2002). In-season fertilizer application occurs mostly from early tillering in June up to flowering in July, with most applications occurring at or prior to panicle initiation. In late August, about five weeks before harvest, growers greatly reduce or eliminate water inflow, allowing water in the field to subside in preparation for drainage. Harvest then occurs late September to mid-October. After harvest, a significant amount of rice straw remains on the field. Rice straw burning is only allowed for disease control. Therefore, straw is usually incorporated, which can be done dry or under flooded conditions. If the incorporation is done dry, a stubble disc is used. Supplemental

irrigation may be needed during the winter to promote decomposition. Under flooded conditions, the fields are flooded as soon after harvest as possible. Early flooding allows more time for decomposition and takes advantage of warmer weather. After the initial flood, the straw is rolled into the soil. After this procedure, the depth of the flood is increased.

Almost all varieties of rice are semi-dwarf and respond to high nitrogen levels. Mineral fertilizer (usually ammonium-based) is applied at an average rate of 147 kg N ha^{-1} yr^{-1}, but can range from 120 to 188 kg N ha^{-1} yr^{-1} (UCCE 1997). Soils in continuous rice production and early plantings usually require a higher N level for optimum plant growth and sustained high yield.

A.2.5. Safflower

A deep, fertile, well-drained soil is required for an optimal safflower yield. Safflower is frequently grown without irrigation as a soil conditioning and weed-control measure on land that otherwise is irrigated. Safflower is thought to be a relatively drought-resistant crop due to its very deep rooting system. However, safflower will not produce a satisfactory crop without adequate soil moisture. The crop is extremely sensitive for rain and fog once the flower buds are formed. Therefore, when additional irrigation is necessary during the growing season, it has to be very short. Safflower grows relatively well in saline soils. However, it is more sensitive to salinity at germination than at later growth stages

Before planting, the entire soil should be sufficiently wet, by rainfall or by pre-irrigation. The planting date ranges from February to early March in the San Joaquin Valley, late February to early March in the Sacramento Valley, and March in coastal drylands. Safflower is often planted late (mid-May to June) in seasonally flooded areas because of crop failure or lack of alternatives. A soil temperature of at least 4˚C is needed for the crop to germinate, but temperatures of 16˚C or higher are ideal. Safflower can survive summer temperatures up to 38˚C to 43˚C, but the yields are generally greater in years with moderate daytime temperatures (24˚C to 32˚C). The growing season usually takes 140 to 170 days. After 120 days, the crop will already be produced, but the remaining time is necessary for seed moisture to reach 8% before it can be harvested. Usually, this occurs 50 to 60 days from peak flowering (early August in the Sacramento Valley region). Early fall rains may cause sprouting of seeds in the unharvested crop, leading to a crop failure. Under late plantings, yields are often reduced by 50% or more compared to optimum planting times at the same location. The fertilization rate on an irrigated safflower field ranges from 84 to 196 kg N ha^{-1}.

A.2.6. Sunflower

In California, sunflowers are grown for seed production or for oil. If the crop is grown for seed, male sunflower plants must be planted in between the female plants to ensure transfer of pollen by bees. After pollination, the male plants are knocked down. Plants that are used for oil production are usually self-compatible. Sunflower can be planted on

a wide variety of soils. Sunflower is a deep-rooted crop which can extract soil water below the root zones of small grain crops. It uses an intermediate amount of water and is considered relatively drought tolerant (Halvorson et al. 1999). The soil should be well-drained and have a high water-holding capacity and a near-neutral pH (6.5 to 7.5). Sunflower plants produce reasonably well on high-stress soils such as those affected by drought, salinity, or moisture. Sunflower can be planted during a wide range of dates, as long as the soil temperature is at least 7.2˚C. A temperature of 10˚C is required for germination. Also, the seedbed should be prepared so that a moist soil environment is available for seed germination and growth. The growing season of a sunflower crop is approximately 120 days. Sunflower is furrow irrigated. Water requirements average 48 cm of water during the growing season, applied in up to six irrigations. The first irrigation can be delayed if the soil is near field capacity at the planting date. Sunflower production usually requires a starter fertilizer if a soil test indicates that there is not enough nitrogen available. During the final cultivation, about 90 kg N ha^{-1} should be side-dressed during the final cultivation (Schmierer et al. 2004). Sunflower seeds are harvested at a moisture content around 9%.

A.2.7. Tomato

Tomatoes are usually grown under contract. They can be planted on a variety of soil textures. Tomatoes are planted over an extended period from January to May. In the Central Valley, fields are planted for fresh market tomatoes from March through July for harvest from June through October. In Southern California coastal counties, spring production fields are planted from mid-January to mid-March for harvest from May through July (Hartz et al., 2008). Sandy soils are preferred for early plantings, due to easier access to the field under wet conditions. In addition, a sandy soil warms more rapidly. On the other hand, loam and clay loam soils are more productive, as long as the soil is well drained and irrigated with care. To accommodate wet soil conditions in the spring, beds are generally made in the fall, allowing for timely planting and reduced soil compaction. Ground preparation prior to listing beds includes subsoiling, disking, and land planing. Most tomato crops are direct seeded on beds. Transplanting is increasing in popularity, but it currently only covers about 30% of the tomato fields in California. An optimal soil temperature for germination is around 20˚C. The development of the plant and the fruit occurs optimally by a daily temperature between 25˚C and 32˚C. Usually, sprinkler irrigation is used during the first growing stages. Later on, furrow irrigation is commonly used. The interval between irrigations ranges between 7 and 14 days. Irrigation should be stopped at least two weeks before harvest. In California, N fertilizer is commonly applied at rates ranging from 140 to 280 kg N ha^{-1}. Maximum yields are attained with N fertilizer rates between 157 and 202 kg N ha^{-1}.

A.2.8. Wheat

Wheat is an annual crop grown during winter. There are no specific soil requirements for wheat. Wheat is considered quite tolerant to wet soils. Small grains are considered more tolerant to shallow soils than other crops, but still, yields are correlated with soil

depth. In Yolo county wheat is planted in the fall (October to December) and harvested from the end of May until the end of August (IPM 2002). A wheat plant needs on average 147 days to maturity. A period of two to five weeks with a temperature above 3˚C is necessary for acclimation to cold weather. After this, seedlings can survive temperatures as low as -19˚C.

About 112 kg N ha^{-1} is applied in October before the growing season (Jackson 2001). The pre-plant nitrogen is sprayed over the field and afterwards incorporated by tillage about two weeks before planting. After planting, most wheat fields are flood irrigated three times between March and May. Wheat crops need on average 15 cm of water during the growing season (Vargas et al. 1999). Another 45 kg of N ha^{-1} is injected in March. One week after harvest during the springtime, crop residues are incorporated by soil tillage. In total, about 160 kg N ha^{-1} is applied (Figure A.6). Values of 60–90 are reported for dryland wheat (ARE 2007). Rates of 125–155 are reported for irrigated wheat (ARE 2007).

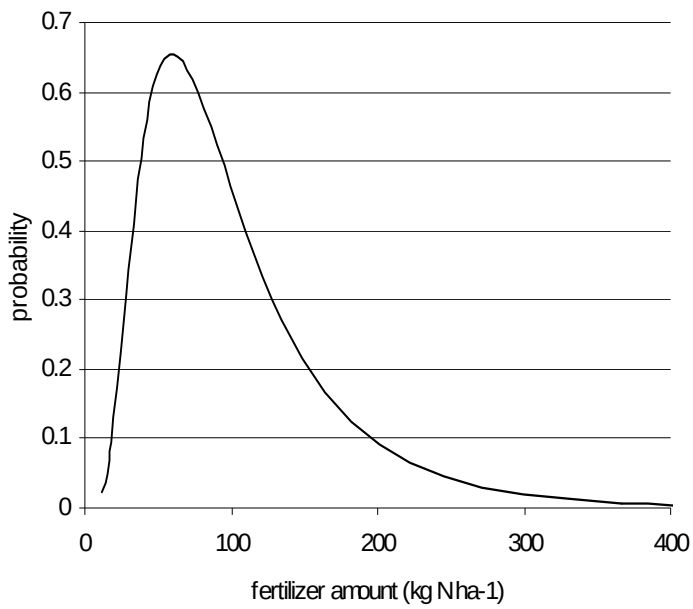

Figure A.6. Probability density function for the fertilizer amount used for wheat

Source: ERS 1995

A.2.9. Crop Rotations

Most crops are grown in a rotation. Direct consultations with farmers in Yolo County reveal that the following are the most typical rotations in this county:

- Tomato – wheat
- Corn – tomato – wheat
- Tomato – wheat – alfalfa – alfalfa – alfalfa – alfalfa
- Sunflower or safflower – tomato – wheat

Rice is usually not grown in a rotation with other crops. Based on USDA statistics, only 30% of California rice is grown in rotation with other crops, and 70% is continuous with occasionally a fallow period. In better-drained soils (usually having lighter textures), rotation crops may include safflower, corn, cotton, oats, wheat, grain sorghum, dry beans, sugarbeets, vegetable seed crops, and tomatoes. However, these alternate crops grown after several successive rice crops may do poorly.

In the Sacramento Valley, safflower is grown in rotation with wheat, tomatoes, barley, corn, cotton, or sugar beets. Safflower is grown commonly in the rice-producing regions of the Sacramento Valley. Safflower benefits from the abundant supply of moisture stored by such soils and does not require additional water. Its ability to dry out these soils to considerable depths improves them for succeeding crops. In the San Joaquin valley, safflower is used commonly in rotation with cotton. The deep root system of safflower creates a better infiltration capacity of the soil, which benefits the next crop in the rotation. Successive safflower crops should not be planted because of the danger of serious damage from rust. Where rainfall averages less than 430 mm or where weeds are a problem, safflower is often preceded by a year of fallow. A continuous sunflower cropping is less productive than a rotation of sunflower with almost every other crop. Rice is typically grown for only one or two years, after which the field is planted to other field or row crops. Regular crop rotation often has the effect of reducing pest control costs and increasing yield. Rotation can also help with straw disposal problems. Because the rice support program restricts which crops can be grown in rotation, farmers need to contact the Farm Service Agency (FSA) to determine the effect on their eligibility (ARE 2007). Corn is usually grown in rotation, but it does follow itself better than most crops. A buildup of diseases is noted in some fields under continuous corn (AGRIC 2007). Normally, wheat, and barley are not grown two or more years in succession, mainly due to build-up of diseases. However, if a summer irrigated crop is grown as a double crop (e.g., with sorghum or corn), wheat and barley can be grown continuously with good results (UCCE 2001).

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