Climate Friendly Farming™ Project Overview and Context

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In 2007 the International Panel on Climate Change (IPCC) concluded that human actions are very likely the main driver for the increasing global temperatures, rising seas, and shifting weather patterns known as climate change. With changes already being felt, the effort to minimize future climate change has become more urgent. Climate change has the potential to negatively impact many of our natural resources and natural resource-based industries, including agriculture, which we depend on to feed the world's population and provide a variety of other environmental benefits.

Agriculture is both a source and a sink for several of the most important greenhouse gases (GHGs) involved in climate change, including methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Possible actions to mitigate these greenhouse gas emissions include strategies to **reduce** greenhouse gas emissions from agricultural systems, and **restore** soil carbon that has been lost from the atmosphere due to agricultural practices. They also include strategies to **replace** fossil-fuel derived products (whose emissions are generally inventoried in other economic sectors) with agriculturally-derived products that are more "carbon friendly."

The Climate Friendly Farming™ (CFF) Project was established to provide research-based information to support agricultural climate mitigation policies and the deployment of "climate-friendly" agricultural practices and technologies by the agricultural sector. The project, funded by the Paul G. Allen Family Foundation along with government and industry grants and contracts, has assessed the greenhouse gas emissions occurring within three of the most common agricultural systems of Washington State, developed concrete strategies for reducing the climate change impacts of agriculture, and provided guidance about how these results might apply to current and future policy efforts.

Greenhouse Gas Sources and Sinks in Agriculture, Global Perspective

Direct greenhouse gas emissions from agriculture are significant, accounting for an estimated 10-12% of total global anthropogenic emissions (IPCC, 2007). However, this figure excludes several types of "indirect" greenhouse gas emissions that are generated in support of agricultural production but accounted for in other sectors, such as agricultural fuel use, emissions from agrochemical and fertilizer production, and emissions from land use changes to produce agricultural products. If these effects are included, it has been estimated that agriculture accounts for 17-32% of total annual global anthropogenic greenhouse gas emissions (Bellarby et al., 2008).[1]

[1] Agriculturally-related electricity and fuel use (included in the buildings and transport sector in national and international inventories) is estimated to account for an additional 0.2-1.8%, emissions related to the production of agrochemicals and fertilizer (included in the industry sector) an additional 0.6-1.2%, and effects resulting from land use changes as additional land is cleared for agriculture (included in the land use change sector) an additional 6-17% (Bellarby et al., 2008).

Likewise, the World Bank (2007) concludes that agriculture accounts for 26-35% of worldwide GHG emissions.[2] Both the magnitude of emissions from agriculture, and the relative importance of different factors, varies widely across different regions of the world (Smith et al., 2007).

Greenhouse Gas Sources and Sinks in Agriculture, National Perspective

In the United States, a national greenhouse gas inventory is carried out annually by the Environmental Protection Agency (EPA), as required under the United Nations Framework Convention on Climate Change (UNFCCC). The estimates from the latest inventory are presented here, as they are the most commonly cited emissions figures. However, it is important to note that the figures presented in the national inventory are constrained by the data available, and dependent on the assumptions that underlie the methodologies used. One of the goals of the Climate Friendly Farming Project is to generate data and methodologies for emissions at the farm level that can be compared to national averages.

According to the most recent EPA inventory, *direct* greenhouse gas emissions from agriculture accounted for approximately 6% of gross national emissions in 2007 (US-EPA, 2009).[3] These emissions are growing, but not as fast as total U.S. emissions; agricultural emissions rose 8% between 1990 and 2007 in the United States, while overall emissions have grown 17% (US-EPA, 2009). As with international estimates, adding *indirect* agriculture-related GHG emissions that are currently accounted for in other sectors raises the total impact considerably; Johnson and Johnson (2006) estimated that adding omitted agriculture-driven sources of emissions raised the estimates of 2003 U.S. emissions from agriculture by 38%, to approximately 10% of all U.S. emissions.[4]

Three important greenhouse gases are emitted by agricultural activities: methane, nitrous oxide, and carbon dioxide. Within the U. S. agricultural sector, methane and nitrous oxide accounted for 46% and 54% of net agricultural emissions in 2007, respectively (US-EPA, 2009). Meanwhile, agriculture was estimated to be a net sink

[2] This figure includes 15% accounted for directly in the agricultural sector according to emissions inventories that governments have submitted to the United Nations Framework Convention on Climate Change, plus emissions from deforestation in developing countries (agriculture is the leading cause of deforestation) (World Bank, 2007). This calculation does not include emissions associated with energy use or production of agricultural inputs.

[3] Agricultural sector emissions were 413.1 MMT CO_2e in the U.S. in 2007, compared to total gross emissions of 7,150.1 MMT CO_2e (US-EPA, 2009).

[4] Johnson and Johnson's (2006) calculation included emissions from livestock facility fuel and power, soil N_2O emissions and fuel use from growth and processing of crops consumed by livestock, energy use by agriculture for machinery, transport, irrigation, etc, and emissions from indirect energy use to produce agricultural inputs including fertilizer, lime, machinery and buildings. They calculate that this raises the portion of emissions due to agriculture from 486.4 MMT CO_2e to approximately 670 MMT CO_2e. The values were converted to % of total emissions using the total for gross 2003 emissions given in the EPA's (2009) Greenhouse Gas Emissions Inventory, 6,981 MMT CO_2e.

for CO_2, though the associated uncertainty is large (US-EPA, 2009). Each of these gases is generated by different sources, some of which are promising targets for mitigation, and others of which are less so.

Methane

Methane (CH_4), responsible for almost half of agriculture's impact, is a much more potent greenhouse gas than carbon dioxide; over 100 years, the global warming potential (GWP) of methane is 25 times that of carbon dioxide (IPCC, 2007). [5] Within agriculture, methane is produced when organic materials decompose in oxygen-deprived conditions, including from enteric fermentation (the digestive process unique to ruminant animals), from stored manures, and from rice grown under flooded conditions (Mosier et al., 1998, as cited in IPCC, 2007). Methane is also released when agricultural residues are burned.

In the United States, the most recent GHG inventory by the EPA estimated that enteric fermentation was the most significant source of methane, accounting for roughly 73% of total methane-related agricultural emissions in 2007, while manure management accounted for 23%. Although manure management is not the most significant source of methane, it is growing quickly; emissions from manure management increased by 45% between 1990 and 2007 (US-EPA, 2009), driven mostly by the increase in liquid manure systems for swine and dairy cattle as production shifts towards larger facilities. In addition, new regulations have shifted manure management at smaller dairies from daily spread towards manure managed and stored on site, which increases methane emissions.

Rice cultivation and burning of agricultural residues each accounted for less than 4% of agricultural methane emissions in the U.S., though these sources are more significant in other regions of the world (US-EPA, 2009; IPCC, 2007).

Nitrous Oxide

Nitrous oxide (N_2O) is an even more potent greenhouse gas than methane, with a GWP that is 298 times that of carbon dioxide over 100 years (IPCC, 2007). [6] Nitrous oxide emissions in agriculture are generated mainly by naturally-occurring microbes in the soil during transformation of nitrogen compounds. Emissions are greatly enhanced when available nitrogen (N) exceeds plant requirements, especially under wet conditions (Oenema et al., 2005; Smith and Conen 2004, as cited in IPCC, 2007). Smaller amounts of nitrous oxide are also generated from manure management under aerobic conditions and from burning of agricultural residues.

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[5] This is the most current GWP, reported in the IPCC Fourth Assessment Report (2007).

[6] This is the most current GWP, reported in the IPCC Fourth Assessment Report (2007).

In the U.S., nitrous oxide emissions are dominated by those from agricultural soils, which in 2007 accounted for an estimated 93% of nitrous-oxide-related emissions from agriculture, and 67% of total N_2O emissions from all sectors (US-EPA, 2009). Other agricultural sources are much less significant, with manure management accounting for about 6% of agricultural N_2O emissions, and composting and field burning of agricultural residues each representing less than 1%. Annual N_2O emissions from agricultural soils fluctuated between 1990 and 2007, without showing any significant long-term trend. Soil nitrous oxide emissions are highly sensitive to the amount of N applied to soils, which has not changed significantly over the time period. They also vary according to weather patterns, soils and crop type (US-EPA, 2009).

Estimations of soil N_2O emissions are particularly uncertain, because N_2O emissions are highly variable, both spatially and temporarily, with yearly variations that are often greater in magnitude than management-induced variations (Clayton et al., 1997; Kaiser et al., 1998, as cited in Del Grosso et al., 2005). The uncertainty range associated with the EPA's point estimation of nationwide direct soil N_2O emissions from agricultural management, the category that accounts for the majority of N_2O emissions from agriculture, was -27% to +54%, from 126.2 MMT CO_2e to 265.2 MMT CO_2e. [7] This high level of uncertainty is consistent with the complexity of the underlying microbial processes and the high spatial and temporal variability (US-EPA, 2009).[8] In addition, the current U.S. inventory assumes that all nitrogen is equally likely to be emitted as N_2O in order to attribute total soil N_2O emissions to various sources (e.g. nitrogen fertilization, manure application, tillage), an assumption which is unlikely to be true (US-EPA, 2009). Uncertainty in estimations of indirect soil N_2O emissions from managed soils is even greater than for direct emissions (Del Grosso et al., 2005), and was -43% to +136% in the most recent U.S. inventory (US-EPA, 2009).[9]

Carbon Dioxide

While all economic sectors emit carbon dioxide (CO_2) to the atmosphere, only agriculture and forestry also absorb it. Carbon dioxide is absorbed from the atmosphere when it is incorporated into plant tissues through photosynthesis, and some of this carbon is later incorporated into stable soil organic matter as plants decompose. Meanwhile, carbon dioxide is emitted from soils through metabolic

[7] MT = metric tons (1 MT = 1 Mg); MMT = million metric tons (1 MMT = 1 Tg)

[8] Uncertainty in direct emissions calculated by modeling with DAYCENT was predicted by Monte Carlo Stochastic Simulation, addressing uncertainties in model inputs and structure, for 95% confidence interval. Uncertainties in direct emissions calculated with the IPCC 2006 Tier 1 methods (a minority of emissions) were estimated with a simple error propagation approach. For comparison, uncertainty associated with emissions from cement production are +/- 13%, and those associated with methane emissions from enteric fermentation are -11%, +18%.

[9] Uncertainty was predicted by Monte Carlo Stochastic Simulation, for 95% confidence interval.

activity of plant roots and respiration of soil microbes that decompose plant litter and soil organic matter.

Net emissions of carbon dioxide from soils are dependent on the balance between carbon gains and carbon losses. The amount of carbon (C) stored in soils is more than three times the amount of C in the atmosphere and 4.5 times the amount of C stored in living plants (Lal, 2004). Therefore, an increase in the size of the soil C pool could significantly influence the trajectory of atmospheric CO_2 concentration (Wang et al. 1999).

In general, agricultural soils have much lower levels of soil carbon than natural systems (Cambardella and Elliot, 1992; Johnson, 1992; Lal et al., 1999; Wang et al., 1999; Purakayastha et al., 2008), with well-documented historical losses from conversion to agricultural use in the Great Plains and Corn Belt (Paustian et al., 1997), as well as dryland eastern Washington (Jennings et al., 1990). In the U.S., a recent review estimated that the average concentration of soil organic carbon in agricultural soil was now 22-36% lower than under native conditions across the U.S., representing C loss that occurred over many decades (Franzluebbers and Follett, 2005). Over long time periods, agricultural soils tend towards a new steady state at much lower soil carbon levels, though they may not reach this point if soil management changes. Evidence suggests that many agricultural soils only stabilize after many decades, and that most agricultural soils may only recently be entering a new steady state (Flach et al., 1997; Paustian et al., 1997).

The latest U.S. greenhouse gas inventory estimated that agriculture was a net sink for CO_2 in 2007 (US-EPA, 2009). However, uncertainty in this measurement is very high, and it is also possible that some categories of soils represent a net source of carbon. For example, the combined uncertainty range for flux associated with agricultural soil carbon stock change in cropland remaining cropland was -152% to +148%, which includes values from 49.6 MMT CO_2e sequestered to 9.4 MMT CO_2e emitted.

It is also critical to note that the inventory does not reflect historical losses of carbon from converting native ecosystems to agriculture. Duxbury (1994) estimated that because of carbon losses, emissions from agriculture have been comparable to those from combustion of fossil fuels over the last 150 years, though fossil fuels are more significant at present. Rebuilding these carbon stocks in soil and vegetation through changes in soil and crop management could be an important climate mitigation strategy.

Greenhouse Gas Sources and Sinks in Agriculture, Washington State Perspective

In addition to carrying out national greenhouse gas inventories, the EPA provides guidance to states for conducting statewide GHG inventories, as well as extensive default data to be used where state-specific data are not available. In Washington State, the most recent statewide greenhouse gas inventory estimated that agriculture accounted for direct emissions of 5.4 MMT CO_2e in 2005, or 6% of GHG emissions (WA-DOE, 2007). Figures that included indirect emissions from agriculture would no doubt be larger. The three main sources were agricultural soils (N_2O, representing 52% of the agricultural emissions on a CO_2 equivalent basis), enteric fermentation (CH_4, 30%), and manure management (mostly CH_4, 17%). While emissions from agricultural soils and enteric fermentation are projected to decline through 2020, emissions from manure management are projected to rise by roughly a third. It should be noted that projections were in most cases based on the assumption that the average historical trend would continue, and that this may or may not be appropriate for a given type of emissions.

Washington agricultural soils were estimated to act as a sink for carbon, storing 1.4 MMT CO_2e annually (WA-DOE, 2007), though the estimates provided in this inventory are drawn from a prior inventory (1997) and are based on limited field-specific baseline soil carbon data that are not well correlated with existing management practices. As with the national inventory, it is important to note that the quality of these estimates relies heavily on the quality of the underlying data. The Washington State inventory relies heavily on state-level defaults provided by the EPA, derived from national estimations. Particularly in cases where there is strong regional or local heterogeneity, modeling parameters that are appropriate for estimating national totals may be inappropriate for making inferences at a smaller regional level (Ogle et al., 2006).

Location, all the consequent factors associated with location, and management can affect both the trend and magnitude of soil organic carbon (SOC) levels, and this heterogeneity is not incorporated well into defaults. For example, Figure 1.1 below shows the relative difference between native and cultivated soils for three common soil series in the dryland production area near Pullman, WA. Figure 1.2 shows the relative difference between native and cultivated soils for nine common soils in the irrigated production area of the Columbia Basin. In the dryland soils, all of the cultivated soils are significantly lower in SOC than native soils, and the magnitude of loss varies with soil type. In contrast, irrigation in the Columbia Basin has led to increases in SOC over native sites in all soils regardless of other management practices, though soil type does influence the magnitude of that increase.

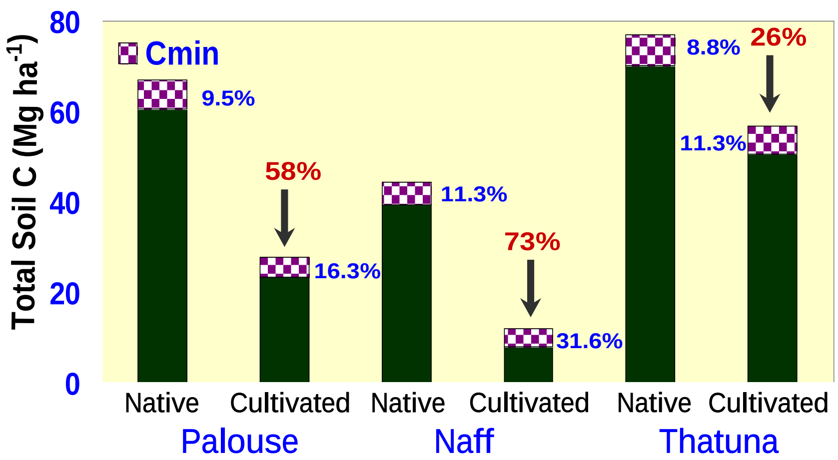

Figure 1.1. Difference in total soil organic C between native and cultivated soils by soil type near Pullman, WA. Soil sample depth was 0-20 cm. Cross-hatched areas of graph (Cmin) represent proportion of total soil organic carbon that was mineralized (converted to CO_2) during a 182-day laboratory incubation. This Cmin indicates soil organic C that is more readily lost through soil disturbance (e.g., tillage). Portions of these data were published by Purakayastha et al. (2008).

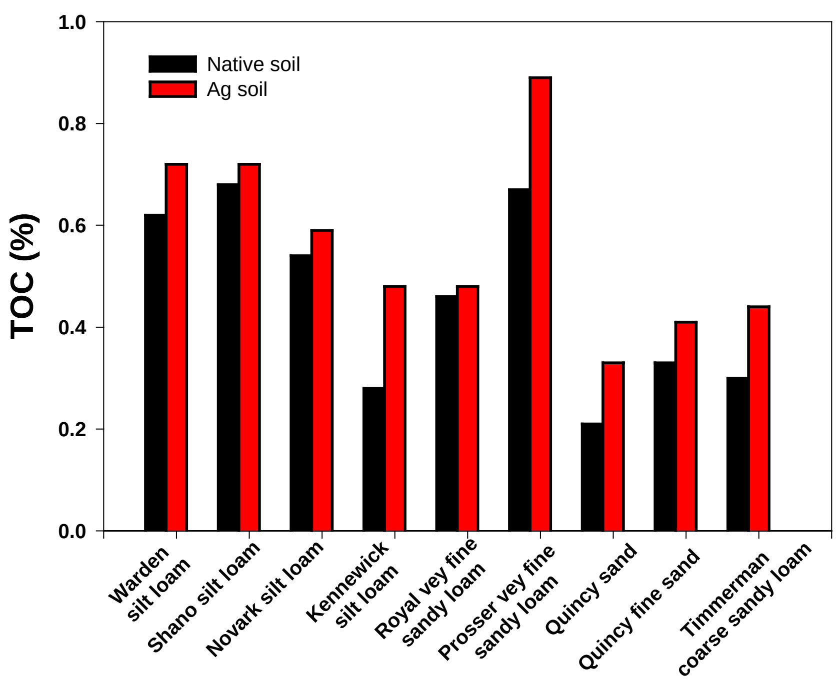

Figure 1.2. Difference in total soil C between native and cultivated soils by soil type in the Columbia Basin, WA. Soil sample depth was 0-30.5 cm. Data are from Rogowski et al. (1999).

Significant differences in SOC are also caused by differences in management strategy, including tillage, residue management, and crop rotation. Figure 1.3 shows the difference in expected carbon input (a key variable in determining trend and magnitude for SOC) for the Cook Agronomy Farm in Pullman, Washington after a switch in crop rotation from a continuous cereal rotation to a cereal- legume rotation. These examples make it clear that generalized inventories of soil carbon may not be dependable tools to use as a basis for agricultural carbon inventories, carbon trading, or mitigation policies.

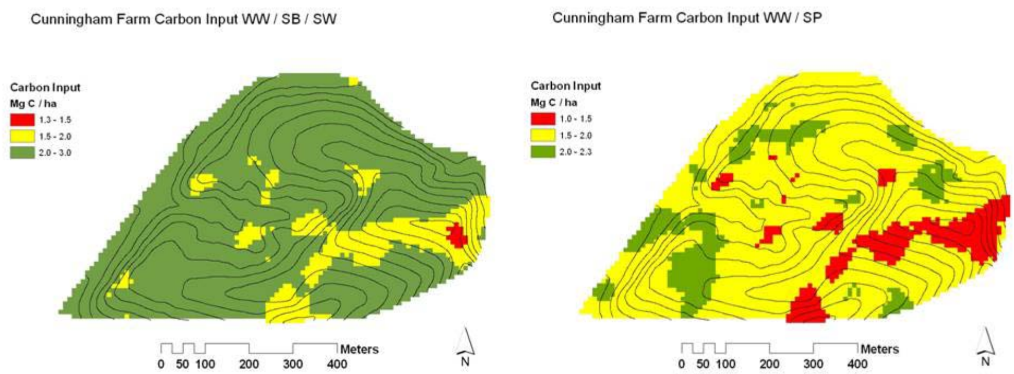

Figure 1.3. Difference in expected carbon input after moving from a continuous cereal rotation (winter wheat-spring barley-spring wheat, on left) to a cereal-legume rotation (winter wheat-spring pea, on right), Cook Agronomy Farm, Pullman, Washington. These data are from D. Huggins (previously unpublished).

Greenhouse Gas Mitigation Strategies

Mitigation opportunities in agriculture include actions that

(1) reduce emissions of N_2O, CH_4, and CO_2
(2) enhance sequestration of CO_2, and
(3) displace emissions in other sectors such as energy (generally CO_2).

Specific strategies include the following, not all of which can be influenced by policy (IPCC, 2007; Smith et al., 2008; Paustian et al., 2004):

<u>Reducing or avoiding emissions of N_2O, CH_4, and CO_2</u>

- Changing agricultural practices on productive, established agricultural lands
- Lowering nitrous oxide emissions, primarily through improving N-use efficiency
- Decreasing methane emissions by capturing or preventing emissions from animal manure storage, improving livestock efficiency, and changing animal diets through additives or other agents
- Increasing the efficiency of farm inputs such as fuel, fertilizers, and pesticides.
- Avoiding the cultivation of new agricultural lands now under forest, grassland, or other non-agricultural vegetation

Restoring or maintaining soil sequestration of carbon (CO_2)

- Sequestering carbon from the atmosphere in agricultural biomass and soils through improved management (including enhanced residue and organic amendments, reduced tillage, increased perennial plantings and agroforestry, crop rotations, improved management of grazing lands, controlling erosion, and other methods)
- Decreasing the rate of land clearing for agriculture and taking marginal lands out of production

Displacing emissions in other sectors such as energy (generally CO_2)

- Increasing production of agricultural biofuels or other bioenergy products to replace fossil energy emissions

Magnitude of Possible Mitigation through Agriculture

While methane and nitrous oxide are currently the primary direct sources of net emissions from agriculture, a full accounting of the mitigation potential from agriculture must also include the potential for sequestration of carbon through reversing the cumulative, historic losses of carbon from the soil to the atmosphere. In fact, the IPCC (2007) has estimated that 89% of the global technical mitigation potential from agriculture (technical potentials refer to that which is physically possible, without considering economic, social, or other barriers to adoption) comes from enhancing soil carbon sequestration, with a much smaller but still important potential from lowering emissions of methane (9%) and nitrous oxide (2%). These mitigation potentials consider only direct agricultural sector emissions, and thus exclude the potential contributions from bioenergy production, as well as indirect mitigation through reductions in energy, fertilizer, and agrochemical use by the agricultural sector.

The estimated potential for the global agricultural sector to mitigate GHG emissions is substantial, with an estimated technical mitigation potential of 5500 to 6000 MMT CO_2e per year by 2030, excluding fossil fuel offsets from bioenergy and indirect mitigation through reductions in agrochemical production and other similar activities (IPCC, 2007; Smith et al., 2008). To put this amount in context, this represents approximately 20% of the total annual global CO_2 emissions during the 1990's (Smith et al., 2008).[10] Uncertainty in this calculation is quite high, with a low estimate of approximately 400 and a high estimate of 10,600 MMT CO_2e per year, due primarily to uncertainty in the per-area estimates for mitigation measures. Not surprisingly, a regional analysis shows that the strategies employed would be quite different in various regions of the world.

[10] Global emissions were approximately 29,000 MMT CO_2e per year during the 1990's (Smith et al., 2008).

Globally, agricultural mitigation options are considered to be cost competitive with non-agricultural options. Economic analysis suggests a global economic potential somewhat lower than the technical potential, but still significant. Specifically, the IPCC (2007) estimates that agriculture could mitigate 1500-1600 MMT CO_2e/yr (approximately 5% of global emissions) in 2030 with carbon prices up to $20/MT CO_2e, [11] with additional mitigation potential at higher prices (IPCC, 2007; Smith et al., 2008). Not surprisingly, the mix of strategies employed varies depending on the price of carbon. At low prices, the dominant strategies would be those consistent with existing production, such as change in tillage practices, fertilizer application, livestock diet formulation, and manure management. Higher prices elicit land use changes that favor bioenergy production and afforestation at the expense of existing production, and also allow for the use of more costly animal feed-based mitigation options (Smith et al., 2008).

As mentioned above, strategies that lower indirect emissions from agriculture, such as activities that lower the use of energy, fertilizer, and agrochemicals within the agricultural sector, are normally excluded from calculations of agriculture's mitigation potential. While this makes it possible to compare mitigation figures with the data presented in national inventories, it can be somewhat misleading, as it minimizes the impact that agricultural producers could have. As one indication of the potential magnitude of these activities, Smith et al. (2008) have estimated that improved energy efficiency in agriculture could achieve additional mitigation of 770 MMT CO_2e/yr (representing 2.5-3% of global emissions in the 1990s) by 2030.

Meanwhile, the mitigation potential for bioenergy is potentially almost as substantial as the potential from all other agricultural strategies, though uncertainty in this estimate is high. The mitigation potential for bioenergy has been estimated at 70-1260 MMT CO_2e/yr in 2030 at prices of $20/MT CO_2e. This represents mitigation of 5-80% of all other agricultural mitigation activities combined (IPCC, 2007; Smith et al., 2008). Thus, through its energy-producing potential and ability to sequester carbon, agriculture, along with forestry and organic waste management, are likely the only economic sectors that have the potential to be a "net sink" for GHGs.

Mitigation Potential, National Perspective

Few comprehensive assessments of mitigation potential are available at the national level. Instead, assessments of technical mitigation potential have often focused on one particular strategy or a group of strategies. For example, soil carbon sequestration on agricultural lands has received considerable attention, as mitigation options are relatively inexpensive to implement and soil carbon stocks respond quickly to management changes (Sperow et al., 2003; Wander and Nissen, 2004). In a comprehensive treatment, Lal et al. (1998) estimated a total technical mitigation potential from carbon sequestration on U.S. croplands of 275-763 MMT

[11] The symbol $ represents U.S. dollars unless otherwise noted.

CO_2e/yr. [12] Similarly, Follett et al. (2001) estimated a technical mitigation potential on U.S. grazing lands of 105-403 MMT CO_2e/yr.[13]

Estimations of the potential of a single carbon mitigation activity fail to account for the fact that when multiple mitigation strategies are implemented simultaneously, mitigation activities may compete with or otherwise interact with each other (Golub et al., 2009; Schneider et al., 2007). They also often fail to consider the simultaneous impact (positive and negative) that mitigation activities can have on nitrous oxide and methane emissions. And estimations of technical mitigation potential fail to account for economic barriers, including impacts on international production levels, trade, and international market prices.

To address these considerations, Schneider et al. (2007) used a sector model to jointly assess a range of competing mitigation options and their impact on agricultural production. At carbon prices below $13.64 per MT CO_2e,[14] the model predicted that soil carbon sequestration through reduced tillage would dominate mitigation efforts, with reduced fertilization, improved manure management, and afforestation also contributing. However, at higher prices, they predicted that bioenergy-related strategies would predominate. These results are similar to the outcomes of a separate modeling effort by Lee et al. (2005).

As might be expected, the economic mitigation potentials predicted by Schneider et al. (2007) are far short of the technical potentials computed by their model. In total, at a cost of $2.73/MT CO_2e, 205 MMT CO_2e were saved through agriculture and forestry, representing roughly 3-4% of total net 1990 U.S. emissions (US-EPA, 2009). [15] An increase to $5.45/ MT CO_2e increased total abatement to about 279 MMT CO_2e (4-5% of total U.S. emissions in 1990).[16]

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[12] Many soil scientists (including Lal) measure and report C, while CO_2e is the unit used to make comparisons across all GHGs, and is the current international standard to express GHG emissions. To make comparisons easier, we have converted all values to CO_2e, but when original authors used another unit, we report that value in a footnote. Emissions of non-CO_2 gasses are translated to CO_2 equivalents using global warming potentials (the IPCC recommends using 100-year GWPs). To convert from C to CO_2e, multiply by 44/12. Lal reported a total technical mitigation potential from carbon sequestration on U.S. croplands of 75-208 MMT C/yr.

[13] 28.5-110.0 MMT C/yr

[14] Likewise, carbon equivalents (CE) were more frequently used in the past for comparing impacts across all GHGs, mostly for agricultural applications. Schneider et al. (2007) analyzed the impact carbon prices above and below $50/MT CE in their analysis. To convert $/unit CE to $/unit CO_2e, multiply by 12/44.

[15] At a cost of $10 per MT CE, 56 MMT CE were saved through agriculture and forestry. The total was converted to a percentage (on a CO_2e basis) of total emissions using U.S. emissions of 6099 MMT CO_2e in 1990 (US-EPA, 2009).

[16] An increase to $20 per MT CE increased total abatement to about 76 MMT CE. The total was converted to a percentage (on a CO_2e basis) of total emissions using U.S. emissions of 6099 MMT CO_2e in 1990 (US-EPA, 2009).

Using a general equilibrium model, Golub et al. (2009) analyzed the mitigation response of the U.S. within the global context, allowing for changes in land use and prices and reallocation of inputs within and across sectors and world regions. According to their modeling, at a global carbon tax of $27.27/MT CO_2e, U.S. abatement within the agricultural and forestry sectors reached a maximum of 770 MMT CO_2e per year over the next 20 years (99 MMT CO_2e from the agricultural sector and 671 MMT CO_2e from forest sequestration).[17] In this scenario, mitigation from the agricultural sector alone represented about 1-2% of total U.S. emissions in 1990, and about 26% of agricultural emissions. [18]

If the tax was implemented in the U.S. alone, then U.S. abatement by agriculture and forestry reached a maximum that was about 4% higher, of 796 MMT CO_2e per year, with much more of the total (139 MMT CO_2e) coming from the agricultural sector (Golub et al., 2009).[19] The smaller abatement potential under a global tax is a consequence of the strong export orientation of agriculture in the U.S., which responds to reduced production in the rest of the world (caused by the global tax) by increasing its own production and hence emissions. Thus, they suggest that analyses that focus on the U.S. alone may generally under-estimate the costs of emissions abatement, by failing to account for the implications of price changes that occur elsewhere in the world.

These analyses illustrate the importance of incorporating economic considerations, at the individual as well as the macro level, into any assessment of mitigation strategies for agriculture.

Mitigation Potential, Washington State Perspective

No comprehensive mitigation potential is available for Washington State. However, in 2008, as part of the work of the Climate Advisory Team appointed by Governor Gregoire, the Agricultural Sector Carbon Market Workgroup (ASCMW), with a variety of stakeholders representing agriculture and environmental interests, prepared a report recommending promising agricultural GHG mitigation strategies for the state of Washington. Work was limited by the charge to focus on mitigation options that could plausibly be incorporated into a market-based mechanism as offsets or credits from a "non-capped" agricultural sector, rather than exploring all potential GHG mitigation options. Using a relatively conservative set of

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[17] According to their modeling, at a global carbon tax of $100/MT CE, U.S. abatement reached a maximum of 210 MMT CE per year over the next 20 years (27 MMT CE from the agricultural sector and 183 MMT CE from forest sequestration).

[18] Agricultural mitigation potential was converted to a percentage of total emissions (on a CO_2e basis) using U.S. emissions of 6099 MMT CO_2e in 1990, and to a percentage of agricultural emissions (on a CO_2e basis) using U.S. agricultural emissions of 384.2 MMT CO_2e in 1990 (US-EPA, 2009).

[19] If the tax was implemented in the U.S. alone, then U.S. abatement reached a maximum that was about 4% higher, of 217 MMT CE per year, with much more of the total (38 MMT CE) coming from the agricultural sector.

assumptions, the ASCMW recommended strategies with the potential to provide 6.96 MMT CO_2e annually from four selected agriculture and organic waste management mitigation practices: (1) precision farming (0.25 MMT CO_2e per year); (2) conservation and grazing lands (3.42 MMT CO_2e per year); (3) co-digestion of manure and food processing wastes (2.6 MMT CO_2e per year); and (4) soil carbon sequestration on working agricultural lands (0.69 MMT CO_2e per year) (Cook et al., 2008).

In total, these strategies represents 129% of 2005 emissions from agriculture in the state, or 7% of *gross* total emissions in the state (total emissions, without accounting for sequestration by forestry and agriculture) (Cook et al., 2008; WA-DOE, 2007). [20]

Where regional analyses have been conducted as part of a national study, results suggest that the mix of strategies will vary regionally, based on local conditions (Schneider et al, 2007). Therefore, policies that allow flexibility will be more successful and more cost-effective to implement, as they permit landowners to choose strategies that make sense in their local context. In Washington State, which contains a diversity of agroclimatic conditions, strategies would need to vary within the state as well.

The Climate Friendly Farming™ Project

The Climate Friendly Farming project was designed to improve estimates of agriculture's current contribution to greenhouse gas emissions in Washington State, develop and deploy technology and management strategies that could be used to lower the climate change impact of agriculture, and provide decision support tools (technology demonstrations, computer modeling tools, and publications) that enable the industry to respond to new policy and market opportunities for GHG mitigation. As a secondary benefit, the strategies investigated also have the potential to improve environmental stewardship through conserving soil, protecting water quality, and recycling nutrients.

The project, which was established in 2003, focused on dairy production, irrigated vegetable farming, and dryland grain production, three farming systems of particular importance for Washington State, but applicable to other areas of the U.S. and the world.

In dairy farming systems, specific mitigation strategies investigated included anaerobic digestion and associated technologies. While other mitigation strategies have been suggested for animal operations, anaerobic digesters (AD) are possible to

[20] Agricultural mitigation potential was converted to a percentage of total emissions (on a CO_2e basis) using WA State emissions of 94.8 MMT CO_2e in 2005, and to a percentage of agricultural emissions (on a CO_2e basis) using WA State agricultural emissions of 5.4 MMT CO_2e in 2005 (WA-DOE, 2007). This comparison with agricultural emissions is provided for comparison of magnitude only. The types of emissions reductions incorporated into the strategies recommended by the ASCMW are not exactly equivalent to the emissions incorporated into the agricultural sector by the WA State GHG Inventory; thus this does not mean that the agricultural sector would have no emissions.

implement in the near- to medium-term. The AD unit functions as the basis of a biorefinery system that has the potential to mitigate GHG emissions through multiple avenues, including reductions in direct emissions that would otherwise occur through lagoon storage of manure, and displacement of emissions in the energy sector through the production of renewable bioenergy. This technology is also a priority because manure management is a quickly-growing source of GHG emissions at both the state and the national level. As part of an effort to address economic and nutrient concerns that constrain adoption of the technology, CFF team members also investigated additional high-value by-products to help offset the cost of anaerobic digesters and to recycle nutrients, including a pilot study of generating purified biogas for use as a transportation fuel.

In dryland and irrigated farming systems, investigations of baseline carbon sequestration and nitrous oxide emissions formed a key area of research. Efforts to design effective climate policies rely on accurate estimations of current emissions as well as estimates of the impact from implementing various mitigation strategies. Thus, the Climate Friendly Farming project aimed to provide scientifically rigorous information to enhance the policy process, using a combination of field data and modeling efforts.

Major mitigation strategies investigated included the impact of conservation tillage, including reduced and no-till management, on soil carbon levels (dryland and irrigated systems), improved cropping systems (crop rotation and residue management for dryland and irrigated systems), and improving nitrogen-use efficiency by tailoring fertilizer inputs to within-field conditions (dryland systems). Soil carbon continues to receive strong interest and may be eligible for carbon credits. Meanwhile, the impacts of N_2O are often overlooked, despite the fact that the potential to deploy management practices and technology to reduce direct N_2O emissions or indirect emissions associated with the production of N fertilizers may have immediate likelihood for success as a GHG mitigation strategy.

The Climate Friendly Farming Project incorporated several smaller research components across all three agricultural systems to explore the potential role of bioenergy production by Washington agriculture. Specifically, researchers collaborated on a statewide inventory of waste biomass sources and investigated the potential of oilseeds, switchgrass, and crop residues as dedicated energy crops.

Combining Applied Biological Systems Engineering and Field Research with Computer Modeling and Economic Analysis

The project was intentionally multi-disciplinary and multi-faceted, combining field research, technology research and development, computer modeling, and economic and policy analysis. Given the expense of sampling and the high spatial heterogeneity in SOC in our region, computer modeling was an essential part of our approach. We applied a cropping systems simulation model, CropSyst (Stöckle et al., 1994; 2003), to evaluate the long-term effects of reduced tillage intensity on net SOC conservation and N_2O emissions for select cropping systems in eastern Washington.

CropSyst

CropSyst is a process-oriented and robust computer simulation model based on mechanistic principles, allowing for applications to a large number of crops in any world location. CropSyst is multi-year and multi-crop, and serves as an analytical tool to study the effect of climate, soils, and management on cropping systems productivity and the environment. I n the CFF Project, emphasis was placed on developing a user-friendly interface and a weather generator, providing links to GIS software, and adding CO_2 and N_2O flux predictive ability.

CropSyst simulates soil-plant-atmosphere water and nitrogen dynamics, crop phenology, canopy and root growth, biomass production, crop yield, residue production and decomposition, soil erosion by water, and salinity. These processes are in turn affected by weather, soil characteristics, crop characteristics, and cropping system management options including crop rotation, cultivar selection, irrigation, nitrogen fertilization, soil and irrigation water salinity, tillage operations, and residue management. Depending on the process, CropSyst calculations are made at hourly or daily time steps. The model has been evaluated and used in the U.S. Pacific Northwest (PNW) (e.g., Pannkuk et al., 1998; Peralta and Stöckle, 2002; Marcos, 1997; Marcos, 2000; Jara and Stöckle, 1999; Stöckle and Jara, 1998; Kemanian, 2003; Kemanian et al., 2007) and in many world locations (e.g., Stöckle et al., 1994, Stöckle et al., 2003; Pala et al., 1996, Donatelli et al., 1997; Stöckle et al, 1997, Stöckle and Debaeke, 1997; Sadras, 2004; Monzon et al., 2006; Wang et al., 2006; Benli et al., 2007; Todorovic et al., 2009).

Other cropping system models have been developed in the U.S., including DSSAT (Jones et al., 1998), EPIC (Williams et al., 1984), and RZWQM (Ahuja et al., 2000), and elsewhere including STIC (Brisson et al., 2003) and APSIM (McCown et al., 1996), but none of them have been tested in the U.S. PNW. In a recent comparison of cropping systems models (van Ittersum and Donatelli, 2003), CropSyst was the only model that calculated biomass gain based on crop transpiration and transpiration-use efficiency, an approach that has been shown to be more robust than the radiation capture and radiation-use efficiency approach used by other models (Steduto and Albrizio, 2005; Steduto et al., 2007; Stöckle et al., 2008). This is particularly important for estimating crop growth and yield as a function of water, an advantage for applications in dryland regions. For more information on cropping systems models, readers are referred to a special issue of the European Journal of Agronomy (van Ittersum and Donatelli, 2003).

Reviews of models for estimating SOC dynamics have been presented by Powlson et al. (1996), Molina and Smith (1998), and Shaffer et al. (2001), including single-pool and multiple-pool models. Multi-pool models, such as CropSyst, separate soil organic carbon into pools with different turnover rates. As discussed by Kemanian et al. (2010), multiple-pool models have several limitations (e.g., SOC has a continuum of chemical and physical characteristics and interactions, making it hard to represent by prescribed pools); nevertheless they have been widely used and proved quite useful for assessing soil carbon evolution. They also provide for a high degree of predictability through their more detailed representation of SOC dynamics.

The Verbene model (Verbene et al., 1990; Whitmore et al., 1997) and the Century model (Parton et al., 1988; Parton et al., 1994) are among the most comprehensive SOC models, allocating SOC into multiple pools with specified decomposition rates and C:N ratios, and with specified transfer coefficients of C (and N) among pools. The Verbene model was designed to simulate soil organic matter dynamics using a multiple pool approach and based on previous efforts by van Veen (e.g., van Veen and Paul, 1981; van Veen et al., 1984), recognizing that although adequate methods to experimentally establish the partitioning of SOC among different pools is lacking, the approach is currently the most promising to describe SOC dynamics on a field scale. The Century model is an ecosystem model developed to estimate soil carbon changes in the top 20 cm of soil and under different types of vegetation including agricultural crops. The model performs calculations using a monthly time step and treats cropping system residue inputs using simple crop growth functions. More recently, a daily-time-step version was developed to allow for the estimation of short-term trace gas fluxes from different ecosystems (Parton et al., 1998). U.S. cropping systems models such as DSSAT (Gijsman et al., 2002) and EPIC (Izaurralde et al., 2006) have incorporated algorithms from Century to allow for the evaluation of carbon sequestration in response to cropping systems. We have followed a similar approach by incorporating soil carbon dynamics concepts from the Verbene and the Century models, increasing the capabilities of CropSyst to estimate SOC sequestration potential in response to cropping systems performance (a function of soil, weather, and management) and its effect on residue input and SOC accumulation and decay.

Additional CropSyst Model Capabilities

In addition to the capabilities to evaluate cropping systems and soil organic carbon dynamics (e.g., Badini et al., 2007), CropSyst was enhanced to assess the effect of climate change on agricultural systems, particularly regarding plant responses to increasing warming and atmospheric carbon dioxide. Concurrently, a weather generator (ClimGen) was further developed during the CFF Project to generate long-term series of synthetic daily weather that are statistically similar to historical weather and to estimate solar radiation and humidity from temperature to enhance historical records from thermo-pluviometric weather stations. These capabilities were utilized to assess the impact of climate change on agriculture in eastern Washington (Stöckle et al., 2009). Given the importance of tree fruit and wine grape production in the state, vineyard and orchard model capabilities were developed (e.g. Oyarzún et al., 2007; Oyarzún et al., 2008) and utilized in the mentioned climate change study and other studies (Scott et al., 2004; Marsal and Utset, 2008).

C-Farm

Although more complex, multi-pool models such as CropSyst provide a high degree of predictability, they have shortcomings in that they require a significant amount of data to properly calibrate and initialize. Single-pool models are much simpler to calibrate and do not require initializing multiple pools. For this reason, we developed C-Farm (Kemanian et al., 2010) as a simplified version of CropSyst that can be used by extension personnel, consultants, and growers in the U.S. PNW and beyond. We believe that a tool such as C-Farm can be mastered with minimum training. The software is available as an Excel file with embedded Visual Basic for Applications code and as a standalone program.

Economic Analyses

Economic analyses were conducted during the CFF Project to help inform policy discussions regarding the potential for adoption under current and possible future economic conditions. In general, economic analyses focused on the profitability of farm enterprise-level investment, but not necessarily on other economic barriers such as securing financing for capital purchases. For anaerobic digester technology, economic analysis was used to better understand which areas of technological improvement would be most likely to improve project economics, thus focusing our engineering efforts. Additional consideration for non-economic barriers (e.g. farmer knowledge base, regulatory concerns, etc.) to adoption may also need to be considered in policy development.

For dryland and irrigated systems, crop budgets were used in combination with CropSyst results to explore profitability under different tillage regimes, with and without carbon credits. Detailed enterprise budgets were created for three study locations representing different rainfall areas of dryland cropping in Washington, plus one location representing irrigated areas of the Columbia Basin. By making these budgets available on line, they are accessible to producers who wish to use them as a decision support tool.

The modeling, Excel tools, and crop budgets created during this project will also facilitate future work to examine the impacts of agricultural GHG mitigation strategies not yet explored in depth, such as changes in crop rotations.

The Policy Context for Climate Friendly Farming

Agricultural mitigation strategies are most likely to be implemented under an international, national, or sub-national policy context that specifically aims to encourage mitigation of greenhouse gases. Although discussions are ongoing at multiple levels, the form that climate policy will ultimately take is unknown. Given this uncertainty, the Climate Friendly Farming Project was designed to generate information that would be useful in a variety of potential policy contexts. In particular, the project was designed to help address the following policy concerns (adapted from Paustian et al., 2004; Smith et al., 2007):

<u>Additionality.</u> Policymakers generally agree that incentives for adoption of mitigation measures should encapsulate actions that go beyond "business as usual." The Clean Development Mechanism of the UN Framework Convention on Climate Change (2008) describes a multi-step methodology for determining additionality in

GHG mitigation projects, including assessment of economic feasibility as well as additional barriers to technology adoption. Given that there is limited regional adoption of most of the technologies and management practices evaluated by the CFF team, it is our assessment that none of these options should be considered business as usual. There is even substantial *in-region variability* in economic and other adoption barriers for given technologies, so that a given practice may be feasible for one producer but not another. Our research focus has been to develop technological and management innovations to help industry overcome existing barriers and to develop decision support tools to facilitate adoption decisions by producers. Much of this work, especially the economic analysis, is also useful for informing discussions around public policy support for agricultural GHG mitigation, but should not form the exclusive lens for determinations of additionality for agricultural GHG mitigation projects in the region.

<u>Observability/Measurement Concerns.</u> Biological systems such as agriculture exhibit substantial variability between (and within) seasons and locations (Smith et al., 2007). Therefore, data about mitigation efforts are necessarily site and time specific which may make the expense of measurement greater than the economic value of the mitigation. Mitigation actions must lead to changes in greenhouse gas emissions that can either be directly measured, or reliably predicted. Through enhancement of CropSyst and the development of C-Farm, the Climate Friendly Farming Project developed accurate and reliable simulation tools to complement direct measurements in our region.

<u>Uncertainty and Heterogeneity.</u> Compared to other global agricultural systems, the PNW shows a high degree of spatial and temporal variability, requiring significant sub-regional and even within-field management adaptations for successful production. This heterogeneity can introduce substantial uncertainty into assessments of SOC or GHG emissions. Adequately quantifying this uncertainty is critical for developing policy actions that can be reliably included in GHG mitigation strategies.. CFF research has helped assess and model spatial and temporal heterogeneity associated with SOC and N_2O fluxes, and has provided several complementary methodologies that can increase user confidence in predictions of SOC change and N_2O emissions.

<u>Variability in Farming Practices.</u> Mitigation actions that make technical or economic sense in one farming system or location may not make sense elsewhere, and actions that effectively reduce emissions in one location may be less effective or even counterproductive in another (IPCC, 2007). Understanding these differences will help state-level policy makers develop policy with the flexibility necessary to allow for different actions in different locations. To aid in this, the Climate Friendly Farming Project included a variety of different farm systems and multiple locations across the state.

<u>Full Accounting/Leakage.</u> Although policy conversations about agricultural mitigation of GHGs often focus on carbon dioxide, most mitigation actions in agriculture have the potential to impact more than one greenhouse gas – in either

complimentary or opposing ways (Koga et al, 2006; Robertson and Grace, 2004, Schils et al., 2005, as cited in IPCC, 2007). A reduction in a "direct" emission may also lead to an increase in an "indirect" emission, or a policy that mitigates GHG emissions in one location may generate additional emissions elsewhere. To support full accounting, the Climate Friendly Farming Project included a significant focus on nitrous oxide, a potent greenhouse gas that is beginning to receive increased attention, but which has previously been overlooked in policy conversations and calculations about GHG mitigation. We also conducted a limited Life Cycle Assessment to provide a more complete picture of GHG impacts of conservation tillage within larger system boundaries.

Timing/Permanence. While some mitigation strategies for agriculture result in permanent decreases in GHG levels, others may result in temporary reductions (Marland et al., 2003; Six et al., 2004, as cited in IPCC, 2007). For example, carbon sequestration can only remove carbon from the atmosphere until the ecosystem maximum is reached, and subsequent changes in management can reverse carbon sequestration gains. Reduction in N_2O and CH_4 emissions, on the other hand, are permanent, as are avoided emissions as the result of agricultural energy efficiency gains or substitution of fossil fuels by bio-energy (Smith et al., 2007). Both temporary and permanent strategies were examined by the Climate Friendly Farming Project, as both have value, but it is important to clearly specify the type of mitigation.

Economic Concerns of Farmers. Farmers make decisions about whether or not to adopt a certain management strategy based on a variety of economic and non-economic considerations. The economic analyses done by the Climate Friendly Farming Project help to clarify the current economic context for designing policy measures. This helps to understand whether there are differences in the economic outcomes based on farm size, crop rotation, or other characteristics. In cases when adoption has not occurred despite favorable economics, it may also suggest that non-economic barriers are significant and need to be addressed.

Ultimately, we conclude that no combination of policy options will likely completely eliminate GHG emissions from agriculture. For example, some amount of N_2O emissions will always be an inevitable byproduct of natural soil processes necessary for producing food. This implies that society as a whole will have to decide what level of GHG emissions is acceptable in order to achieve the level of production considered necessary. However, the fact that some agricultural GHG emissions may be necessary should not be seen as a reason for inaction. To the contrary, we hope that our research will contribute to a realization that agriculture can make a strong contribution to mitigating GHG emissions. In fact, many of these mitigation strategies can be implemented in the near term, without compromising our ability to meet food production, economic, and other environmental goals.

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