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Agricultural Offset Potential in the United States

Economic and Geospatial Insights

Jeremy Proville, Robert Parkhurst, Steven Koller, Sara Kroopf, Justin S. Baker and William A. Salas

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Agricultural Offset Potential in the United States: Economic and Geospatial Insights

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Abstract

Although agricultural greenhouse gases (GHGs) are emitted from a wide variety of activities and regions, many mitigation opportunities exist. This article describes efforts undertaken by Environmental Defense Fund (EDF) and partners (2007 to present) to convert abatement opportunities into carbon offsets with the aim of reducing GHGs in this sector and providing revenue to landowners. Analyses of emission-abating practices for rice, rangelands and almonds demonstrate that abatement costs are significant for most practices and are accompanied by high break-even carbon prices — often due to high transaction costs. Nonetheless, total abatement potential is shown to be large for certain activities. For this reason, and given the large series of opportunities not yet explored, a focal point of subsequent efforts should be to reduce transaction costs and barriers to entry.

Keywords

Agriculture, carbon offsets, United States

JEL classification numbers

Q50, Q18

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Contents

1. Introduction

Agricultural activities account for an estimated 10–12% of global anthropogenic greenhouse gas (GHG) emissions and 56% of non-CO_2 GHG emissions (Pachauri et al. 2014). In terms of climate policy, this effectively means that it is important to recognize that agriculture forms a significant share of global emissions and to explore mitigation opportunities for the sector. There is a deep body of literature documenting mitigation approaches across many crops (see Eagle and Olander 2012; Biggar et al. 2013), activities and regions; analysis suggests that technical GHG emissions abatement potential in the global agriculture sector is high, with enough biophysical potential to offset 20% of total emissions economy-wide by 2030 (Smith et al. 2008). However, economic considerations make realization of this full potential unlikely. Recognizing that agricultural activities are critical to meeting needs in terms of food provision and welfare, forms of regulation aiming to mitigate emissions for this sector have been, and continue to be, a controversial and challenging policy question (Godfray et al. 2010; Frank et al. 2017). Nonetheless, there is a clear and important need to link this sector with climate policy initiatives and mitigation efforts that are underway, both in achieving the Paris Accord goals and beyond.

Offset credit mechanisms provide an opportunity to link both of these activities. They are designed to allow entities seeking to reduce their GHG emissions (voluntarily or for compliance) to achieve this indirectly, by compensating another actor for mitigation achieved elsewhere. This is not a novel concept. The idea of emissions “offsetting” dates back to the Clean Air Act Amendments of 1977 (Gorman and Solomon 2002), and GHG emissions offset mechanisms were first piloted as a result of negotiations during the first Conference of the Parties (COP 1) in 1995 (Calel 2013). Since then, offset mechanisms have been used across a variety of settings and sectors. Perhaps the most widely known and highest-volume application relating to land use activities is the Reducing Emissions from Deforestation and forest Degradation (REDD+) program administered by the United Nations, where the total amount of offsets purchased through 2014 was 87 million $tCO_{2e\text{-}100}$ (World Bank Group 2016). Here, a framework was created to incentivize sustainable forest management in developing countries through the creation and sale of offsets.

After the passage of Assembly Bill 32 (AB32) in California, the state’s Global Warming Solutions Act of 2006 that regulates GHG emissions, Environmental Defense Fund (EDF) and partners made a strategic effort to pursue opportunities to include agricultural carbon offset protocols in California's cap-and-trade program. The goal was to provide regulated firms with additional flexibility and options in terms of offset supply, while at the same time creating revenue-generating opportunities for interested agricultural producers. This would also allow the sector to play a role in mitigating emissions, leading to a great deal of learning experiences and novel scientific output along the way.

Throughout this process and across a variety of grants, opportunities were explored for rice and almond farms, as well as for rangelands and grasslands. These spanned a variety of geographies but were largely concentrated in the United States, with a specific focus in California to try to enable offset credits to be allowed under the state's cap-and-trade program. While several papers are currently being written about the scientific and policy aspects of the work carried out by EDF and its partners in this area, this paper highlights lessons learned and data gathered on economics and technical analyses of these offsets.

2. Rice

Rice is a critical crop from a global perspective — it accounts for approximately 19% of global dietary energy (Ray et al. 2013), and as such is the world's third-largest crop by volume of production (USDA Foreign Agricultural Service 2018). It is also important in the U.S., where it accounts for 1.3% of total annual crop sales. California's Sacramento Valley produces 26% of the domestic supply, primarily for sushi, and 72% is produced in the Midsouthern U.S. states of Arkansas, Louisiana, Mississippi, Missouri and Texas (USDA National Agricultural Statistics Service 2012). Rice cultivation is a fairly GHG-intensive activity in comparison with other crops, and this is largely associated with its irrigation needs. Production worldwide accounts for 5–20% of total methane emissions (Sanchis et al. 2012), much of which is emitted as a byproduct of organic decomposition under flooded paddies (Mosier et al. 1998).

While California produces a minute share of total global GHG emissions (1% across all sectors, 0.06% for the agricultural sector and 0.001% for rice production, for a 100-year global warming potential time horizon), it has set a goal to further reduce its emissions to 1990 levels by 2020 on a statewide basis through AB32 (IPCC 2007; ARB 2011). In 2015, Gov. Jerry Brown issued an executive order to establish a more ambitious target of 40% below 1990 levels by 2030. As a result, there are multiple opportunities for farmers to pursue management regimes that reduce

GHG emissions and that have the potential to be sold as offset credits into California's cap-and-trade market. A wide range of methods are documented in the agronomic literature and may be applicable to Californian rice producers. Some of these can be carried out during the growing season (Yagi et al. 1997; Aulakh et al. 2001; Smith and Conen 2004), while others are applied during the off-season (Kang et al. 2002; Xu et al. 2003).

In 2007, EDF saw an opportunity to explore prospects for rice farmers in California to reduce emissions and contribute offsets to the state's cap-and-trade system. In partnership with the California Rice Commission, Applied GeoSolutions LLC, and Dr. Daniel Sumner (UC Davis), EDF was awarded a Conservation Innovation Grant (CIG) (EDF 2010) to achieve this goal. In 2011, EDF expanded these efforts with a second CIG (EDF 2015), awarded to explore the potential of bringing the remaining large share of U.S. rice supply, located in Midsouthern states, into offset markets. This grant was developed and administered in partnership with Winrock International and leading Arkansas rice industry associations and producers. What follows is a summary of the research conducted on economic and technical aspects of these two grants.

2.1 Assessment of abatement potential

As with most offset crediting mechanisms, the first stage involves scoping the suite of management practices that are understood to provide GHG reductions, and to develop scientifically robust estimates of these that could be used as a basis for issuing credits. For rice, as with many of the other project areas discussed in this article, we relied upon the DeNitrification-DeComposition (DNDC) biogeochemical model (University of New Hampshire 2012). Project partners at Applied GeoSolutions LLC calibrated and validated this model using the best experimental data available: 6,316 fields were simulated for 16 farming practices, specific to the Californian region and the Calrose rice variety. Here, primary GHG emissions (carbon dioxide, methane, nitrous oxide) and yields were estimated for the majority of rice-producing acreage in the state, thus enabling further analysis of the GHG changes afforded by switching between management scenarios.

Emissions analysis with DNDC involves trade-offs between long- and short-term climate forcers. Throughout this article, carbon dioxide equivalent in terms of a longer 100-year time horizon (CO_{2e-100}) are presented, yet it is important to remain aware of the short- and long-term trade-offs in the case of certain crops such as rice where these can be more important.

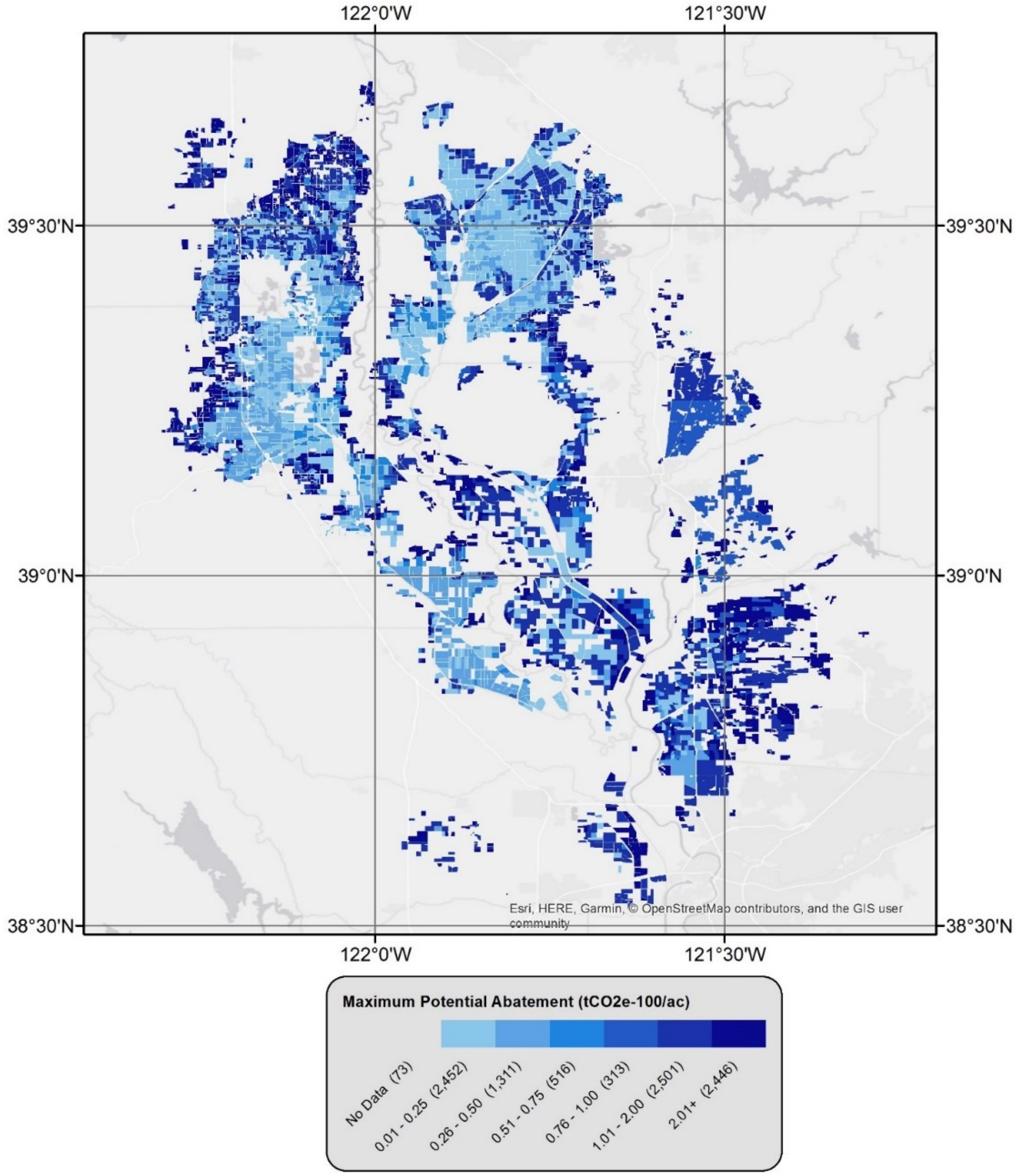
Our study focused on estimating the abatement potential and costs of a suite of the most promising practices. These are: dry-seeding rice fields (as opposed to wet-seeding via aerial delivery), baling harvest residue and hydroperiod adjustments (draining fields in midseason and/or before harvest, and/or reducing winter flooding). We carried out the same process out for Midsouthern states, with a notable difference being the management scenarios that apply in the different climate and geographical settings here.

To explore abatement potentials adequately, the baseline practices must first be characterized — i.e., which management practice is the prevailing one for each modeled land unit? From this point of departure, we can start modeling alternative scenarios and resulting changes in GHG fluxes, yield revenue and costs. For California, this was relatively straightforward as the majority of rice producers follow a variant of the same baseline practice: wet-seeding, with paddies flooded for most of the growing season, and leaving crop residue on fields during the off-season. The one significant factor differentiating growers in the Sacramento Valley, however, is that just over half (~60%) leave fields flooded over the winter months, while the rest do not. This was an important factor to baseline correctly, and was performed by using remote sensing products (Landsat 5 and 7) over a 5-year period to determine the prevailing tendency on a field-by-field basis (Torbick and Salas 2015). For the Midsouth, the most prevalent baseline practice is continuous flooding on dry-seeded fields with normal drainage and residue incorporation on a rice-soy rotation.

Our analysis of physical abatement potential uses model simulations of rice management practices on each field, and then initially indicates which practice combination would yield the most GHG abatement for that particular unit, regardless of economics. For instance, because of certain soil characteristics, a rice field might achieve greater GHG reductions by both dry-seeding and baling, but not with early (preharvest) drainage of the flooded paddy. In this case, abatement from dry-seeding and baling only would be included in the estimate for that field. Similarly, a different field may have maximum abatement by practicing only early drainage — note that some practices are mutually exclusive, while others are additive. The estimates in Figure 1 depict maximum abatement levels, achievable by pursuing the best possible practice combinations across all fields.

FIGURE 1

Map of maximum annual abatement potential of low GHG practices for rice in California's Sacramento Valley



Note: Number of regions in each bin denoted in brackets.

Table 1 outlines aggregate statistics associated with Figure 1.

TABLE 1

Summary of abatement potential of low GHG practices for rice in California's Sacramento Valley

Rice management practice	Maximum potential abatement ($tCO_{2e\text{-}100}$/yr)	% of total abatement potential
Replacing wet-seeding with dry-seeing (drill-seeding)	260,800	44
Early drainage	151,500	25
Rice straw removal (baling)	187,100	31
Total	599,400	100

Note: Baseline from 2008–13 remote sensing imagery. Abatement estimates rounded to the nearest 100 $tCO_{2e\text{-}100}$.

For Midsouthern states, we did not conduct the analysis at a field level, but rather used regions that have a combination of soil characteristics and county boundaries. This was governed by limitations in input datasets and was the most reasonable unit of analysis for use in DNDC. A map of maximum abatement potential is depicted in Figure 2, while Table 2 provides added detail of summary statistics.

FIGURE 2

Map of maximum annual abatement potential of low GHG practices for rice in Midsouthern U.S. states

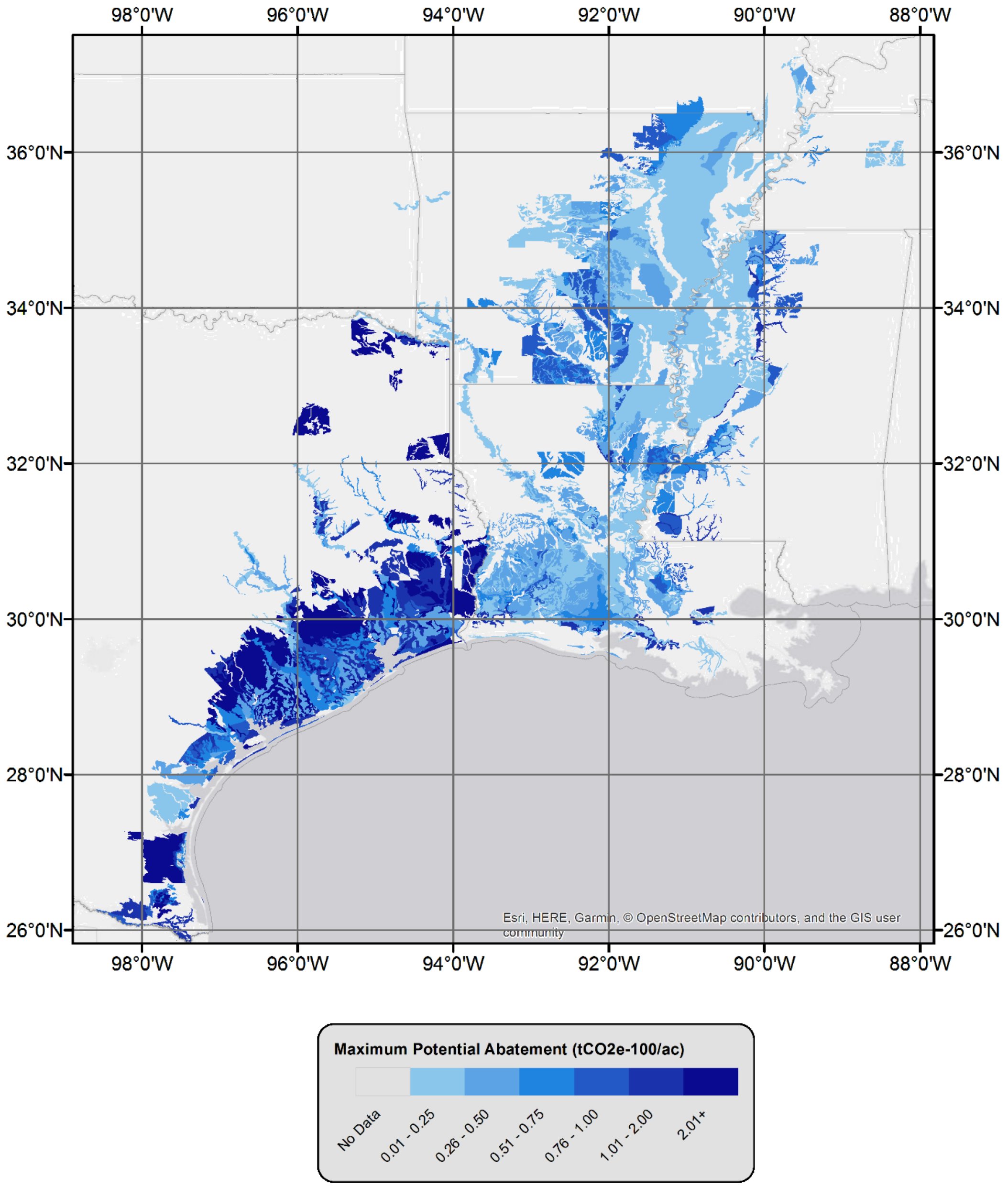


TABLE 2

Summary of abatement potential of low GHG practices for rice in Midsouthern U.S. states

Rice management practice	Maximum potential abatement (tCO_{2e-100}/yr)	% of total abatement potential
Alternate wetting and drying	325,800	13.2
Early drainage	4,900	<1
Rice straw removal (baling)	2,137,300	86.6
Total	2,468,200	100

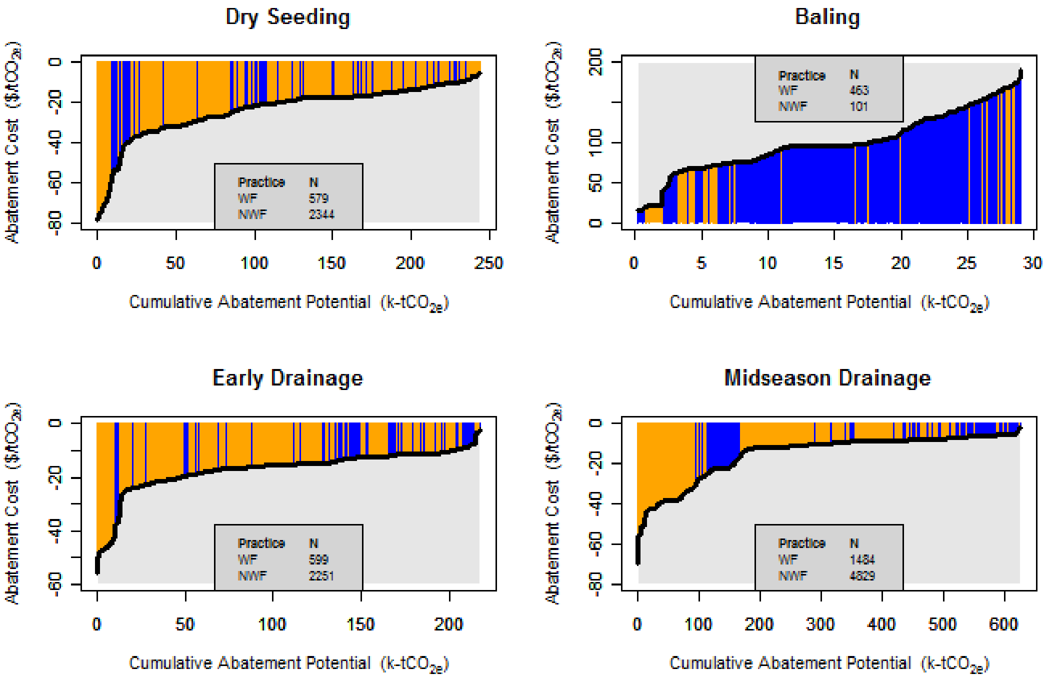
2.2 Economic analysis

We then added an economic layer onto this preliminary analysis by developing an understanding of the expected savings, costs and net profits for each of the management scenarios. We estimated these through the combination of a literature review (Mutters et al. 2004, 2007; Greer et al. 2012) and consultation with farmers and farm advisers.

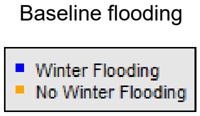
For California, the granularity of field-level data allowed these costs to be combined with abatement estimates to generate marginal abatement cost curves for each practice (Figure 3). Here, the blue/yellow colors describe the baseline designation for each field (blue where winter flooding predominated and yellow where it did not).

FIGURE 3

Marginal abatement cost curves for California rice GHG-reduction practices



Abbreviations: N, number of fields; WF, winter flooding; NWF no winter flooding.



Our results indicate that three of the four practices have negative abatement costs, with averages ranging from -$29.45/acre to -$0.45/acre, while one practice, baling, has a positive average cost of $120.53/acre. Note that these figures represent only the costs of changing farm management and do not factor in revenue changes. In terms of yield impacts, most practices were expected to remain largely similar according the DNDC model (±0.1% change from the baseline). The one exception here was dry seeding, which showed an average 4.5% decrease in yield.

Putting the practice costs and yield impacts together, we can imagine a scenario where we have a carbon market in place and a carbon price of 10$/t (the California spot price at the time this work was carried out). In this instance, we'd find that with an average ~0.7 t/acre reduction, most rice growers would be looking at potential revenue from the market on the order of ~0.5% of their overall crop sales revenue (typically ~1,500 $/acre), or ~2.6% of their net profit (~250$/acre, not including further potential gains from the negative abatement costs of certain practices and locations). Unfortunately, in context of the overarching farm economics, this makes for a fairly weak incentive. If we now change the scenario in favor of a carbon price closer to today's social cost of carbon (42$/t), we find that the potential revenue from participating in the market rises to ~2% of crop revenue and ~11% of net profit. At this stage, the incentive appears a lot more robust, which tells us that from a social standpoint and with a strong price signal, the market could be viable, yet, as it stands conditions are falling short of this.

Onto this we must then layer additional transaction costs associated with the offset market, namely monitoring, reporting and verification (MRV) fees. These typically ended up being fairly significant on a per-grower basis - approximately 14 $/acre for an average 1,000 acre California farm. This amounts to double the average potential revenue from credits at a market price of 10$/t, and with a higher price corresponding to the social cost of carbon, it represents nearly 50% of potential revenue. A series of efforts at EDF revolved around illustrating the need to allow project aggregation, so that MRV costs could be spread across multiple producers and economies of scale achieved. One of the challenges involved with aggregation involves finding ways to streamline verification processes: this was deemed possible for some practices (such as wet/dry seeding, detectable with 93% accuracy via remote sensing), but less so with others. See File 1 (supporting information) for a breakdown of costs and revenues by practice, and Deliverable 11 (USDA 2015) for detail on operational constraints such as MRV.

A major caveat to the economic analysis and cost budgets presented in this article is that the risk perceptions of growers are difficult to quantify and are not captured herein. We have estimated the changes in capital, labor, and direct and indirect costs at farm level, but a significant factor to consider is producers' willingness to accept before shifting cultivation practices. In many cases, growers perceive risks in yield reduction or are currently managing their operations in a way that they feel is optimized. As such, some may be unwilling to make even small changes to their operations. While this paper generally presents the economics in terms of direct savings and costs, we have also conducted surveys and behavioral research to better understand these less quantifiable risk factors for almond growers; this is discussed in a later section.

2.3 Policy and implementation

Several conclusions can be taken from our analysis on rice. First, there appears to be a subset of viable alternative practices for rice producers in California to reduce their GHG footprint while saving on costs. Notably, the two best options are dry-seeding and draining fields early before harvest — across California, these can provide 244 $ktCO_{2e\text{-}100}$/yr and 218 $ktCO_{2e\text{-}100}$/yr of potential abatement, respectively. Soil and infrastructure constraints, as well as a greater potential for yield instability between years, are challenges associated with dry-seeding.

Another important caveat in this analysis is that N_2O emissions were potentially underestimated by DNDC. This is not a flaw of the model, but rather the calibration and validation stages did not reflect an emerging understanding that peaks in N_2O emissions may have been chronically underestimated in field studies to date. Some of the practices explored (dry-seeding, drainage regime changes) require decreased flooding and increased fertilizer use, and if not properly considered, the increased N_2O emissions can exceed the achieved CH_4 reductions (Kritee et al. 2018). Nonetheless, across comparable levels of fertilizer application questions remain as to why certain practices have not been more widely adopted where feasible. This warrants further research in determining the quantitative and qualitative barriers that are limiting farmers from adopting such practices.

In the Midsouth, dry-seeding is already widely implemented and therefore does not represent a shift from the baseline, while growers are starting to investigate and implement alternate wetting and drying. However, two irrigation management scenarios (alternate wetting and drying cycles, as well as early drainage of fields before harvest) appear to provide some abatement potential. Both of these practices have the co-benefit of reduced water use.

The most significant source of potential GHG reductions comes from removal of rice straw, carried out after harvest by baling residue on fields. Nonetheless, given that rice straw can be an important source for forage and habitat of wintering bird populations, EDF commissioned a report to further research this topic (Sesser et al. 2016). The array of potentially significant resulting impacts on bird populations from baling residue was deemed too critical to consider pursuing this option, despite the large potential for GHG reductions.

In May 2013, the California Air Resources Board (CARB) initiated the process for adopting rice offset credits as a formal compliance mechanism for AB32 obligations. Following efforts by five technical working groups and two board meetings, the protocol was successfully adopted on

June 25, 2015, effectively becoming the first crop-based agriculture offset for California's cap-and-trade program. Unfortunately, no compliance credits had been adopted as of September 2020. While the adoption of practices has negative abatement costs, the transaction costs are significant. We developed a model for calculating the costs of developing rice offset projects and determined that these typically outweigh the potential revenue from compliance bodies, with the verification accounting for the largest cost — as much as 50% of the total.

From an environmental outcomes perspective, Haya et al. (2020) conclude from a recent in-depth analysis of the rice protocol that a risk of overcrediting persists. This will be challenging to overcome in the current standardized protocol approach used by CARB.

3. Rangelands

Rangeland is one of the most widespread land uses in the U.S.: grasslands account for 29% of the country's total land area (USDA Foreign Agricultural Service 2018), with much of this essential to livestock grazing. Critically important given their share of the total area is the fact that rangelands represent massive carbon sinks. From a biophysical standpoint, this provides a mechanism to capture and store atmospheric carbon via sequestration in soil and plant matter (Silver et al. 2010; DeLonge et al. 2013), although the degree of sequestration and permanence remain uncertain. Nonetheless, EDF embarked on two CIG studies — in 2010 with Terra Global Capital and in 2015 with the Climate Action Reserve — to investigate potential crediting systems on rangelands. Large portions of the analyses described below were performed by Justin Baker and colleagues at the Research Triangle Institute.

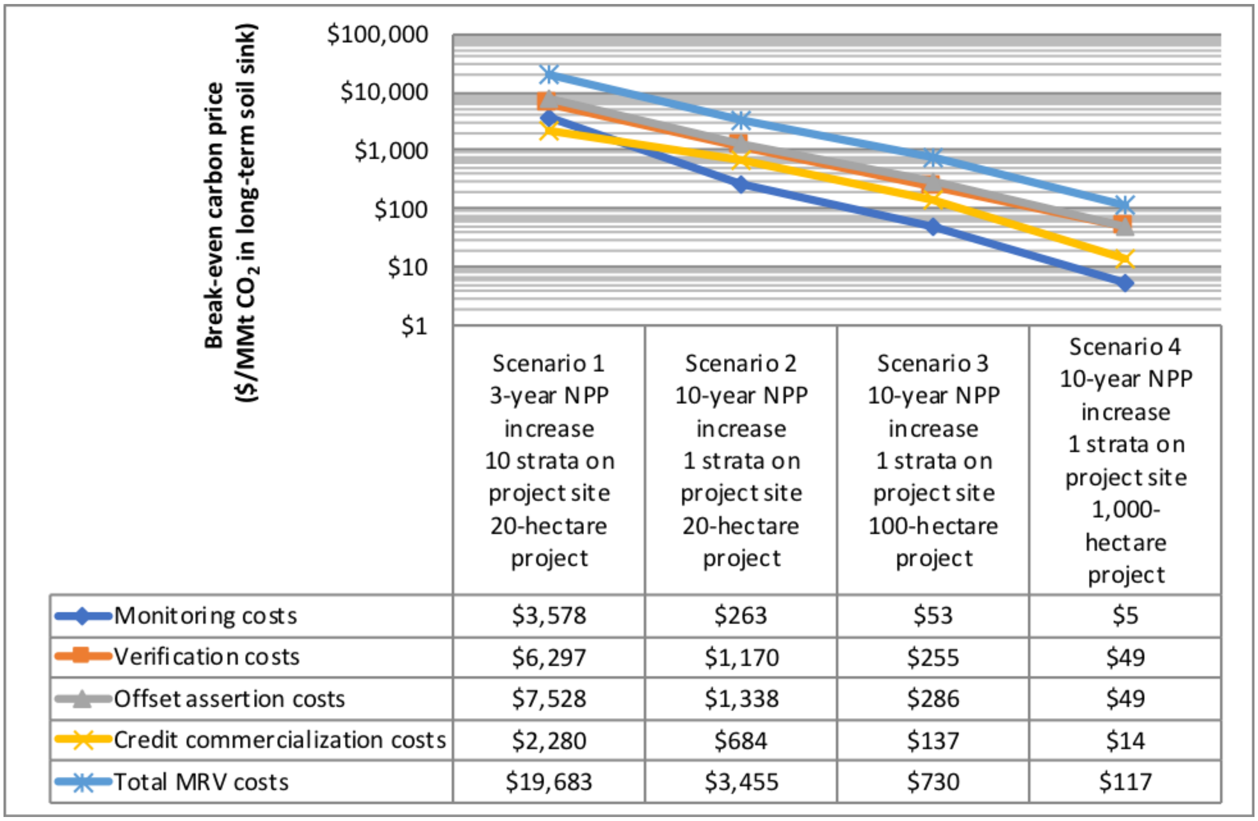
3.1 Composting on grasslands

The first analysis examined the practice of amending compost additions to grazed grasslands to boost primary productivity and sequester carbon into soils. By way of a thorough literature review and consultations with experts, a life cycle GHG assessment tool was developed in order to understand the costs, benefits and break-even carbon prices of this practice. The study explored a representative grazing operation in Marin County, California, to illustrate how GHG emissions, total costs and break-even carbon price incentives can vary with changes in key biophysical, economic and offset protocol parameters. This model (see Supporting information, file 2) serves as a prototype accounting tool for evaluating compost addition projects and could be extended to alternative locations with different biophysical parameters or baseline management assumptions. Sensitivity analysis was performed to evaluate the impact of changing key variable values on GHG and economic outcomes. Key results are summarized below:

- Carbon offsets generated from the production of compost are cost effective across all the scenarios analyzed, but on-farm compost addition is a high cost and significantly variable GHG mitigation source on a $/$tCO_{2e}$ basis when including recent estimates of MRV costs ($117–19,683/$tCO_2$; Figure 4). In most cases, as with rice projects, verification accounted for approximately half the total development cost.
- Whether compost application is a net source or a net sink of GHGs depends on which sources and sinks are recognized and factored into the crediting protocol, as well as other key biophysical parameter assumptions.
- The productivity benefits of compost application on grazing lands may compensate for the cost of the compost purchases and application costs.
- To generate carbon offsets from compost applications, the sources and sinks included must result in a net reduction in GHGs and MRV costs must be very low.
- Break-even carbon prices can be reduced significantly (between three and four orders of magnitude) by altering the requirements and associated costs of MRV (Figure 4). This clearly mandates the need to focus on this transaction cost as a barrier to adoption for this type of offset.

FIGURE 4

Break-even carbon prices required to compensate for the MRV costs of increased soil carbon from compost additions across a representative series of projects



	Scenario 1 3-year NPP increase 10 strata on project site 20-hectare project	Scenario 2 10-year NPP increase 1 strata on project site 20-hectare project	Scenario 3 10-year NPP increase 1 strata on project site 100-hectare project	Scenario 4 10-year NPP increase 1 strata on project site 1,000-hectare project
Monitoring costs	$3,578	$263	$53	$5
Verification costs	$6,297	$1,170	$255	$49
Offset assertion costs	$7,528	$1,338	$286	$49
Credit commercialization costs	$2,280	$684	$137	$14
Total MRV costs	$19,683	$3,455	$730	$117

Note: ‘Strata’ refers to the activity of sampling soil in a project to monitor carbon sequestration levels and account for variability on the land.

A description of the life cycle assessment spreadsheet model and further detail is included in the Supporting information, file 2.

3.2 Avoided conversion of grasslands

The second component of the economic analysis focused on the practice of “avoided conversion of grasslands.” This involves compensating landowners with a credit for resisting the land use change in converting grasslands to croplands. This is a persistent problem throughout the U.S. but is particularly acute in the Prairie Pothole Region, where economic pressures are high. Here, conversion rates between 2006 and 2011 were as high as 5.4% annually (Wright and Wimberly 2013).

The analysis study area centered on the Prairie Pothole Region, and Kansas, Montana, Nebraska, North Dakota and South Dakota in particular. We undertook geospatial modeling to understand the likelihood of conversion, potential land use change emissions and the potential costs of avoided grassland conversion. We also performed sensitivity analyses around key variables such as additionality thresholds for conversion. More detail can be found in the associated published manuscript (Baker et al. 2020). The main findings of this effort were that:

- Significant offset potential (10–40 $MMtCO_2$/yr) is found in this area of the U.S., but at a fairly high cost per unit of emissions reduction ($7–55/$tCO_2$).
- Establishing appropriate additionality criteria has important implications for total project costs and mitigation potential.
- Results from logistical regression models can be used to map areas with a high probability of conversion. In turn, this can aid prioritizing outreach efforts.
- Using rent differentials (i.e., grassland versus other land uses) to establish additionality criteria can be an important mechanism to limit land eligibility and control total program costs. Furthermore, using improved tools for predicting economic rents would allow for increased accuracy in determining regional or local additionality criteria.

3.3 Policy and implementation

From a general standpoint, these analyses underline the fact that the rangeland practice of adding compost to grasslands currently represents a rather expensive form of abatement, exhibiting high break-even carbon prices. While the avoided conversion of grasslands initially represented an expensive form of abatement, the Climate Action Reserve has developed a streamlined approach to create offsets. One of these has gained traction, with eight projects being created by carbon offset project developers and 15,450 credits generated (CAR n.d.). Nonetheless, the key variable driving any of these practices is the verification cost. This is a temporary barrier to widespread adoption, and is surmountable with the aid of targeted efforts pertaining to policies (e.g., project aggregation) and technologies (e.g., remote sensing). The analyses also highlight the need for very clear structures and parameters around protocols if they are to be successful. Critical factors (e.g., additionality threshold for avoided conversion) can have a significant impact on the viability and environmental consequences of the protocols.

4. Almonds

In 2015, EDF was awarded two grants to explore abatement and offset credit opportunities for almonds: a Specialty Crop Block Grant, administered by the California Deptartment of Food and Agriculture; and a CIG, with partners the Almond Board of California, American Carbon Registry, Applied GeoSolutions, Carbon Credit Solutions, Climate Action Reserve, Coalition on Agricultural Greenhouse Gases, Delta Institute, K·Coe Isom, United Suppliers, UC Davis and Viresco Solutions. This section describes economic analyses that formed part of these two bodies of work.

The scope of work focused on almond production in California, largely because this is where the majority of U.S. production originates. The state accounts for 100% of domestic commercial supply and 80% of global commercial supply, and almonds are the second most valuable crop in California, with $5.9 billion in farmgate value in 2014, and one of the top three crops in the state by acreage (Almond Board of California 2016; Macaulay and Butsic 2017). As with our analyses on rice, we began with biogeochemical modeling (again using DNDC) for this region, after first identifying a panel of potential management practices through UC Davis research. These were largely focused on nitrogen input changes, since increased efficiency of nitrogen use reduces GHG emissions and improves water quality. However, reducing nitrogen without field-specific considerations can be risky, potentially impacting the yield and quality of almonds. Designing scenarios for DNDC relied heavily on the UC Davis research, which takes these considerations into account (Alsina et al. 2013; Smart et al. 2014).

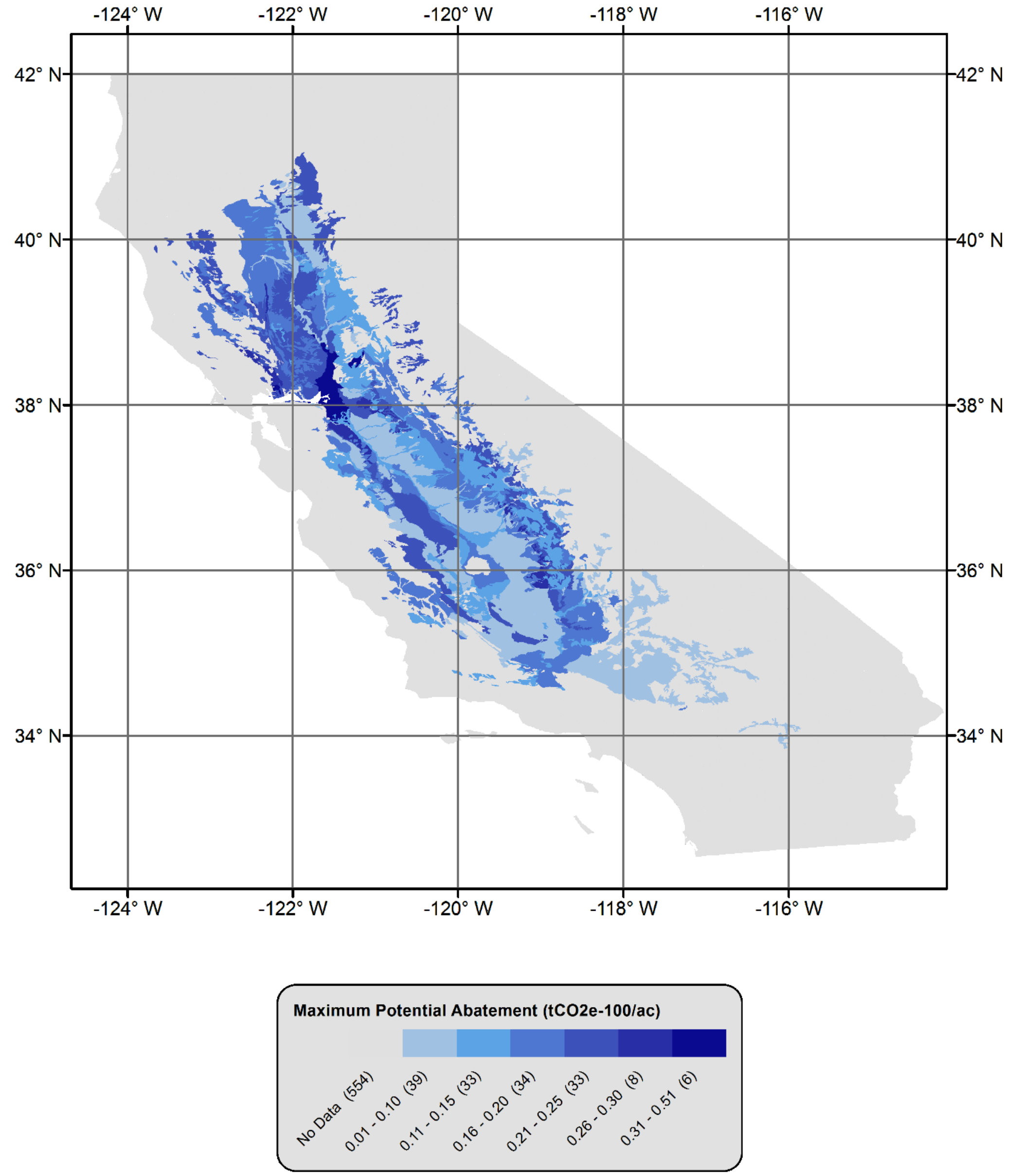
After being calibrated and validated for the crop and geography, DNDC simulated emission and yield changes across 12 potential fertilizer and irrigation management scenarios for 900 representative soil-type location units across the state. Unlike rice, it proved challenging to develop an abatement potential map for almonds as the baseline did not comprise a blend of two practices, but rather the many different ways almonds are cultivated across the orchards of California's central valley. Thus, we defined a baseline for each modeled land area as a weighted average of the various practices employed. We took data for the weighting factors from a report by SureHarvest for the Almond Board of California's California Almond Sustainability Program

(SureHarvest pers. comm.; CASP 2017) to create a breakdown of practices employed by growers across the state.

Once the baseline definition was complete, we estimated maximum abatement potential by selecting the practice offering the highest reductions in GHG emissions by map unit and calculating the difference from baseline emissions. The aggregate value across the entire state was ~175,000 $tCO_{2e\text{-}100}$/yr; Figure 4 depicts the spatial attributes of these potential reductions. The figures are significantly lower than those found in rice, using the same overall analytical approach. A large part of this can be attributed to the fact that baseline emissions are typically much higher for rice paddies, given that they can be flooded year-round and emit methane accordingly. Almond growers tend to optimize their management, especially in terms of fertilizer, as the high value of the crop makes this worthwhile.

FIGURE 5

Maximum annual abatement potential for low GHG practices in California almond orchards



Note: Number of regions in each bin denoted in brackets.

To build a deeper understanding of the economics of switching between practices, we built a spreadsheet-based tool (see Supporting information, file 3). This allows a grower to compare the costs, returns and emissions of their current practices to those of a range of alternative practices.

A hypothetical carbon price then gives the grower a dollar amount they might see as a return to adopting GHG mitigating practices. The baseline budget is put together using both preloaded values and cost inputs by the growers themselves. The preloaded estimates were obtained from sample budgets produced in 2016 by the University of California Cooperative Extension, and cover most general (representative) costs for the northern and southern parts of the San Joaquin Valley, as well as the Sacramento Valley (Greer et al. 2012). Adjustable values include fertilizer and water costs, baseline yield rate and orchard size, price received for product and the hypothetical price of carbon. One limitation is that these cost budgets assume a sample orchard size of 100 acres; the results presented below could vary depending on farm size.

In general, we found that the practices leading to the highest degree of abatement involved the use of drip irrigation, a 20% reduction in nitrogen application rates, and the use of a calcium ammonium nitrate fertilizer rather than the urea-based alternative. The practice costs associated with changing management toward any of these factors can be considered very low (or even a savings) in the context of total costs in an almond orchard — including amortized capital outlay to implement drip irrigation systems. Nonetheless, a major potential cost associated with these practices is yield impact and foregone revenue. This is of particular concern to almond growers and crop advisers, and this risk perception would likely severely limit uptake of offset credits for reducing GHG emissions in almonds. As there are no prior protocols associated with almonds, this grant did not explore the role of verification costs. Nonetheless, based on data from other crop-based protocols it is quite likely that verification costs would significantly raise break-even carbon prices, given low per acre abatement opportunities.

4.1 Behavioral barriers to adoption

Survey-based behavioral research was conducted within the scope of the CIG. This sheds light on representative levels of interest among growers for a GHG crediting scheme in corn and almond farming (see Supporting information, file 4). In general, there was a roughly equal distribution among the sample of 35 long-form interviewees between viewing the concept of a credit system positively, negatively and neutrally. Results indicate that, while environmental considerations may not be adequate motivation for the widespread uptake of conservation practices, a program could be successful if it had the proper financial rewards.

In general, corn farmers appeared to be more receptive to a GHG crediting scheme than almond farmers, with the latter citing the sensitivity of almonds to nitrogen rates and the high per unit value of almonds as factors limiting their interest. Both groups in the study reported feeling satisfied with their current nitrogen regime and limited knowledge of carbon offset markets. Another key insight picked up was that interviewees' program participation would be heavily influenced by commodity prices. If a given credit is issued at a fixed return over time, interest in the program will wane as commodity prices climb, and vice versa.

The study also included a van Westendorp price analysis to try to identify the range of prices within which credit payments would be "acceptable" to corn growers (i.e., their willingness to accept). The range is delineated by the price that would be too low to be considered worthwhile and what price would be too high to be considered legitimate. The range of acceptable payments was found to be \$18.00/acre to \$37.60/acre. These estimates assume program participation would require no additional investments and would not impact variable production costs or yield outcomes.

Some surveyed growers expressed concerns about the time commitment required by program implementation and compliance. Specifically, growers believed participation would require more than two hours per year, the time commitment included in the survey prompt. It would be valuable in future surveys to obtain a better understanding of the number of hours a grower might be willing to commit annually toward a carbon crediting program based on nitrogen management.

Beyond behavioral aspects, other transaction costs and barriers to adoption that limit the widespread use of such protocols are fairly well documented. Niles et al. (2019) provide a good discussion of these and propose a method to overcome certain limitations, namely the creation of an "umbrella" protocol that can lead to streamlining and accelerating protocol implementation across a wide range of crops and geographies.

5. Conclusions

The large body of work summarized in this document serves to provide a rough characterization of the empirics associated with each crop and geography studied. Most importantly, however, it shows how each piece fits into the larger narrative of a series of efforts to pioneer agricultural GHG offsets in the U.S.

Many lessons were learned at each step of this process. For rice, we found that a significant amount of technical abatement potential is achievable in terms of methane emissions: ~0.6 $MMtCO_{2e\text{-}100}$/yr in California and ~2.5 $MMtCO_{2e\text{-}100}$/yr in Midsouthern states. Because many of the practices explored involve reducing irrigation and flooding, cost changes often relate to decreasing water use; all practices except for baling were found to have negative abatement costs. Yield and revenue projects illustrated that, without a high carbon price, incentives to participate in the market are low for the average producer. Going further, when evaluating offset project development costs, the largest cost — in some cases reaching approximately 50% of the total development cost — was found to be the verification cost of the credits. Nonetheless, the CARB used rice in its first crop-based offset protocol pioneering work into generating opportunities for agriculture to participate in California's cap-and-trade program.

Exploring the opportunities for amending compost additions to rangelands showed that the economic viability of this type of offset is quite low given the high transaction costs. Much of this is associated with MRV costs; reducing these is a critical focus in the design of this and any other type of offset. We also examined factors associated with crediting the avoidance of grassland conversion, and found high abatement potential (10–40 $MMtCO_2$/yr) but also a rather high abatement cost (\$7–55/tCO_2). Efforts by the Climate Action Reserve to develop an emission factor approach applicable to the conterminous U.S. have contributed to reducing these costs dramatically.

For almonds, abatement prospects were a great deal narrower: maximum potential reductions across California amounted to ~0.18 $MMtCO_{2e\text{-}100}$/yr. In this context, high crop value means that growers tend to have fewer opportunities for reductions and display risk aversion to changing management. Although abatement costs may be quite low at the scale of an orchard, large transaction costs remain.

The various types of offsets described in this document all have several common threads. A major one is the role of administrative and transaction costs. MRV (especially verification) costs can clearly be a significant barrier to the economic viability of any given offset. In the context of an agricultural sector, these activities can be even more challenging as they often involve low reductions per acre and require detailed information to estimate emission reductions given by the complex biogeochemical processes involved. Another barrier to adoption relates to supply side characteristics: a multitude of private actors each contribute a small share of overall credit supply, creating a challenge in terms of enrollment and overcoming behavioral hurdles (i.e.

additional ‘switching’ costs). Finally, as with all offsets, market failures such as overcrediting and leakage can arise and must be carefully considered.

Despite the challenges described in the research in this paper, the agricultural sector presents opportunities for contributing to climate solutions. Pursuing these approaches can yield the double dividend of creating new incentives to abate GHG emissions from agriculture and providing new sources of revenue to landowners. Further research should focus on reducing barriers to adoption and improving market design for the more promising abatement opportunities that exist, while exploring new ones for other crops and geographies.

References

Almond Board of California. (2016, June). *California almond industry facts*. Retrieved 2018 from https://www.almonds.com/sites/default/files/2016_almond_industry_factsheet.pdf

Alsina, M. M., Fanton-Borges, A. C. and Smart, D. R. (2013). Spatiotemporal variation of event related N_2O and CH_4 emissions during fertigation in a California almond orchard. *Ecosphere*, *4*(1), 1–21.

Aulakh, M. S., Wassmann, R., Bueno, C. and Rennenberg, H. (2001). Impact of root exudates of different cultivars and plant development stages of rice (*Oryza sativa* L.) on methane production in a paddy soil. *Plant and Soil*, *230*(1), 77–86.

Baker, J. S., Proville, J., Latané, A., Cajka, J., Aramayo-Lipa, L. and Parkhurst, R. (2020). Additionality and avoiding grassland conversion in the Prairie Pothole Region of the United States. *Rangeland Ecology & Management*, *73*(2), 201–215.

Beck Ag. (2016). *Nitrogen Fertilizer Efficiency Carbon Credits program individual depth interviews insights*. Report Commissioned by Environmental Defense Fund.

Biggar, S., Man, D., Moffroid, K., Pape, D., Riley-Gilbert, M., Steele, R. and Thompson, V. (2013). *Greenhouse gas mitigation options and costs for agricultural land and animal production within the United States*. Department of Agriculture Climate Change Program Office, ICF International. Retrieved on September 22, 2020, from http://climatechange.lta.org/wp-content/uploads/cct/2015/03/GHG_Mitigation_Options_USDA.pdf

Calel, R. (2013). Carbon markets: A historical overview. *Wiley Interdisciplinary Reviews: Climate Change*, *4*(2), 107–119.

CASP (California Almond Sustainability Program). (2017). *California Almond Sustainability Program online system*. Almond Board of California. Retrieved September 24, 2020 from https://www.sustainablealmondgrowing.org

ARB (California Environmental Protection Agency — Air Resources Board). (2011). *California greenhouse gas emissions inventory 2000–2009*. Retrieved 2018 from https://www.arb.ca.gov/cc/inventory/data/data.htm

CAR (Climate Action Reserve). (n.d.). *Projects*. Retrieved August 1, 2018, from https://thereserve2.apx.com/myModule/rpt/myrpt.asp?r=111

DeLonge, M. S., Ryals, R. and Silver, W. L. (2013). A lifecycle model to evaluate carbon sequestration potential and greenhouse gas dynamics of managed grasslands. *Ecosystems*, *16*(6), 962–979.

Eagle, A. J. and Olander, L. P. (2012). Greenhouse gas mitigation with agricultural land management activities in the United States — a side-by-side comparison of biophysical potential. In Donald L. Spark (Ed.), *Advances in agronomy. Vol. 115* (pp. 79–179). Academic Press.

EDF (Environmental Defense Fund). (2010). Creating and quantifying carbon credits from voluntary practices on rice farms in the Sacramento Valley: Accounting for multiple benefits for producers and the environment. Retrieved 2018 from https://www.nrcs.usda.gov/Internet/FSE_DOCUMENTS/stelprdb1044916.pdf

EDF (Environmental Defense Fund). (2015). *Demonstrating GHG emission reductions in California and Midsouth rice production*. Retrieved 2018 from https://www.edf.org/sites/default/files/report_usda-cig-emission-reductions.pdf

Frank, S., Havlík, P., Soussana, J.-F., Levesque, A., Valin, H., Wollenberg, E., … Obersteiner, M. (2017). Reducing greenhouse gas emissions in agriculture without compromising food security? *Environmental Research Letters*, *12*(10), 105004. https://doi.org/10.1088/1748-9326/aa8c83

Godfray, H. C. J., Beddington, J. R., Crute, I. R., Haddad, L., Lawrence, D., Muir, J. F., … Toulmin, C. (2010). Food security: The challenge of feeding 9 billion people. *Science*, *327*(5967), 812–818. https://doi.org/10.1126/science.1185383

Gorman, H. S., & Solomon, B. D. (2002). The origins and practice of emissions trading. *Journal of Policy History*, *14*(3), 293–320.

Greer, C. A., Mutters, R. G., Espino, L., Buttner, P., Klonsky, K. M., DeMoura, R. L. and Tumber, K. P. (2012). *Sample costs to produce rice, Sacramento Valley, rice only rotation*. Cooperative Extension, Department of Agricultural and Resource Economics, University of California, Davis. Retrieved September 22, 2020, from http://rice.ucanr.edu/files/196601.pdf

Haya, B., Cullenward, D., Strong, A. L., Grubert, E., Heilmayr, R., Sivas, D. A. and Wara, M. (2020). Managing uncertainty in carbon offsets: insights from California's standardized approach. *Climate Policy*. https://doi.org/10.1080/14693062.2020.1781035

IPCC (Intergovernmental Panel on Climate Change). 2007. *Climate change 2007: Mitigation of climate change*. Working Group III report. IPCC.

Kang, G., Cai, Z. and Feng, X. (2002). Importance of water regime during the non-rice growing period in winter in regional variation of CH4 emissions from rice fields during following rice growing period in China. *Nutrient Cycling in Agroecosystems*, *64*(1–2), 95–100.

Kritee, D. N., Zavala-Araiza, D., Proville, J. Rudek, J., Adhya, T. … Hamburg, S. (2018). High nitrous oxide fluxes from rice indicate the need to manage water for both long- and short-term climate impacts. *Proceedings of the National Academy of Sciences*, *115*(39), 9720–9725. https://doi.org/10.1073/pnas.1809276115

Macaulay, L. and Butsic, V. (2017). Ownership characteristics and crop selection in California cropland. *California Agriculture*, *71*(4), 221–230.

Mosier, A., Kroeze, C., Nevison, C., Oenema, O., Seitzinger, S. and Cleemput, O. van. (1998). Closing the global N_2O budget: Nitrous oxide emissions through the agricultural nitrogen cycle. Nutrient Cycling in Agroecosystems, 52(2–3), 225–248. https://doi.org/10.1023/A:1009740530221

Mutters, R., Greer, C., Klonsky, K. M. and Livingston, P. (2004). Sample costs to produce rice, Sacramento Valley, rice only rotation. Cooperative Extension, Department of Agriculture and Resource Economics, University of California, Davis.

Mutters, R. G., Greer, C. A., Klonsky, K. M. and Livingston, P. (2007). *Sample costs to produce rice*. Cooperative Extension, Division of Agriculture and Natural resources and Department of Agriculture and Resource Economics, University of California, Davis.

Niles, M. T., Waterhouse, H., Parkhurst, R., McLellan, E. L. and Kroopf, S. (2019). Policy options to streamline the carbon market for agricultural nitrous oxide emissions. *Climate Policy*. https://doi.org/10.1080/14693062.2019.1599802

Pachauri, R. K., Allen, M. R., Barros, V. R., Broome, J., Cramer, W., Christ, R., ... and Dubash, N. K. (2014). *Climate change 2014: Synthesis report*. Contribution of Working Groups I, II and III to the fifth assessment report of the Intergovernmental Panel on Climate Change (p. 151). IPCC.

Ray, D. K., Mueller, N. D., West, P. C. and Foley, J. A. (2013). Yield trends are insufficient to double global crop production by 2050. *PloS One*, *8*(6), e66428. https://doi.org/10.1371/journal.pone.0066428

Sanchis, E., Ferrer, M., Torres, A. G., Cambra-López, M. and Calvet, S. (2012). Effect of water and straw management practices on methane emissions from rice fields: A review through a meta-analysis. *Environmental Engineering Science*, *29*(12), 1053–1062.

Sesser, K. A., Reiter, M. E., Skalos, D. A., Strum, K. M. and Hickey, C. M. (2016). Waterbird response to management practices in rice fields intended to reduce greenhouse gas emissions. *Biological Conservation*, *197*, 69–79. https://doi.org/10.1016/j.biocon.2016.02.021

Silver, W. L., Ryals, R. and Eviner, V. (2010). Soil carbon pools in California's annual grassland ecosystems. *Rangeland Ecology & Management*, *63*(1), 128–136.

Smart, D. R., Stockert, C., and Scow, K. (2014). Spatial constraints on N_2O emissions and microbial activity during drip irrigation of perennial crops. *Soil Biology and Biochemistry, n Revision (Cif 3.67).*

Smith, K. A. and Conen, F. (2004). Impacts of land management on fluxes of trace greenhouse gases. *Soil Use and Management*, *20*(2), 255–263.

Smith, P., Martino, D., Cai, Z., Gwary, D., Janzen, H., Kumar, P., ... Rice, C. (2008). Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society of London B: Biological Sciences*, *363*(1492), 789–813.

Torbick, N. and Salas, W. (2015). Mapping agricultural wetlands in the Sacramento Valley, USA with satellite remote sensing. *Wetlands Ecology and Management*, *23*(1), 79–94.

University of New Hampshire. (2012). *The DNDC model.* Retrieved September 22, 2020, from http://www.dndc.sr.unh.edu

USDA (United States Department of Agriculture) National Agricultural Statistics Service. (2014, May). *2012 census full report.* Retrieved 2018 from https://www.agcensus.usda.gov/Publications/2012/#full_report

USDA (United States Department of Agriculture) Economic Research Office. (2017, May 1). *Commodity costs and returns*. Retrieved May 1, 2017, from https://www.ers.usda.gov/data-products/commodity-costs-and-returns

USDA (United States Department of Agriculture) Foreign Agricultural Service. (2018, May). *World agricultural production*. Retrieved 2018 from https://www.fas.usda.gov/data/world-agricultural-production

World Bank Group, International Finance Corporation. (2016, October). *REDD market overview*. Retrieved 2018 from https://www.ifc.org/wps/wcm/connect/dda359c6-b67c-4598-8534-b26ea1b260df/FINAL+REDD+Market+Factsheet+10-17.pdf?MOD=AJPERES

Wright, C. K. and Wimberly, M. C. (2013). Recent land use change in the Western Corn Belt threatens grasslands and wetlands. *Proceedings of the National Academy of Sciences*, *110*(10), 4134–4139.

Xu, H., Cai, Z. C. and Tsuruta, H. (2003). Soil moisture between rice-growing seasons affects methane emission, production, and oxidation. *Soil Science Society of America Journal*, *67*(4), 1147–1157.

Yagi, K., Tsuruta, H. and Minami, K. (1997). Possible options for mitigating methane emission from rice cultivation. *Nutrient Cycling in Agroecosystems*, *49*(1–3), 213–220.

Supporting information

File 1. Breakdown of costs and revenues for rice management practices. [link to file].

This spreadsheet was assembled based on results from DNDC modeling surrounding biophysical outcomes (notably emissions and yields) for each practice. This was combined with research from cost budgets and consultation with extension service experts to assemble estimates of overall practice costs, as well as potential revenues from various sources. Average values for each practice, across all fields were summarized in this spreadsheet.

File 2. Spreadsheet model: life cycle GHG assessment tool for compost amendments on rangelands. [link to file].

This life cycle GHG assessment tool was developed as a prototype accounting tool for evaluating compost addition projects, delineating the costs, benefits and break-even carbon prices of composting on grasslands. The workbook is designed to model the potential net costs of compost application and associated GHG impacts to inform the development of a carbon credit protocol. A variety of parameters are used in the model, including compost attributes, ecosystem response, manure attributes, landfill waste attributes, compost production, transportation, feed production, livestock, feed attributes, project costs, monitoring, validation, GHG offset assertion, credit commercialization and key sensitivities. The model is not intended to be used to estimate the actual costs of carbon credits generated by a particular project. It includes a user interface for the model, calculations used to estimate net costs, tables and coding to support the user interface, figures, and a table for sensitivity analysis in the report.

File 3. Spreadsheet model: nutrient management GHG emission cost-benefit calculator for almonds. [link to file].

This tool is designed to help growers assess the costs and benefits associated with sustainable management practices for almond orchards. A series of eligible practices were researched and assessed using a simulation model to take into account biophysical factors such as soil type, weather, fertilizer management, etc. While this is an approximation of reality, it is designed to provide a rough characterization of the expected yields and GHG emissions given by any practice combination at a given site. Using a grower's specific site information and assumptions, the calculator assesses the cost budget and potential revenue changes (both for yield and GHG credits) given by a shift in management.

File 4. PDF slides: nitrogen fertilizer efficiency carbon credits program survey study (Beck Ag 2016). [link to file].

This slide deck delineates the results obtained from a survey administered to corn and almond producers, on the topic of enrollment to a hypothetical nitrogen efficiency carbon market.