The Water Report

Water Rights, Water Quality & Water Solutions in the West

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ARIZONA GROUNDWATER POLICY

ADDRESSING THE SUPPLY PARADOX

by Fred Breedlove with contributions from:
William Staudenmaier, John Burnside, and John Habib, Snell & Wilmer (Phoenix, AZ)

Introduction

The Arizona Department of Water Resources (ADWR) has published extensive studies of groundwater resources in Arizona. These studies confirm that Arizona has hundreds of millions of acre-feet of groundwater located in more than 40 different groundwater basins across the state. Groundwater in many of the basins extends thousands of feet below land surface, including in the aquifers beneath the Phoenix metropolitan area. Richard, S.M., Reynolds, S.J., Spencer, J.E., and Pearthree, P.A., 2000, *Geologic map of Arizona: Arizona Geological Survey,* Map 35, scale 1:1,000,000, https://ngmdb.usgs.gov/ngm-bin/pdp/zui_viewer.pl?id=7099 (last visited July 19, 2023).

However, while a huge resource, this groundwater is almost entirely a non-renewable water supply (i.e., very little water is added to most of the state's aquifers each year to offset ongoing withdrawals from basins). Because of this limited natural recharge, some of Arizona's more extensively developed groundwater basins experienced significant declines in water tables in the second half of the 20th Century. This prompted the Arizona Legislature to enact the 1980 Groundwater Management Act (Groundwater Code) which was intended to slow, and ultimately end, groundwater declines and related problems such as land subsidence and fissuring. Arizona Revised Statutes (A.R.S.) Sections 45-401, et seq. [Editor's Note: Earth fissures are fractures or cracks that form in alluvial basins due to substantial groundwater overdrafts that produce local subsidence (Holzer, 1976; Jachens and Holzer, 1979; Larson and Péwé, 1986).]

Arizona Groundwater in the News

While the local and national news outlets flood the media with articles about the dire nature of Arizona's water supplies, careful planning by Arizona's water leaders over decades has created resilient responses to these challenges that are unmatched in the Southwest and perhaps the nation. Arguably, Arizona is much better positioned to withstand the challenges of drought and climate change than any state that relies largely on groundwater supplies or any other single water source. However, complex issues are rarely conveyed accurately in news headlines. It's much easier and attention-grabbing for a headline writer to say, *"Arizona is Running Out of Water"* than it is to say, *"Arizona Has Plenty of Water but It's Being Proactive by Taking Important Steps to Ensure the State Develops using Renewable Water Supplies."*

Arizona is taking the heat from national media because it is following decades-old policies designed to shift reliance from non-renewable groundwater to renewable supplies through reasonable, incremental steps. It is these steps that led ADWR to announce in June 2023 that it would no longer allow subdivision development in the Phoenix area to grow by relying exclusively on groundwater. ADWR, *Phoenix AMA Groundwater Supply Updates,* https://azwater.gov/phoenix-ama-groundwater-supply-updates (last visited July

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Smart Irrigation

“CLIMATE SMART” IRRIGATION

ADDING IRRIGATION MODERNIZATION AS A “CLIMATE SMART” PRACTICE A CASE STUDY IN BUILDING A COORDINATED, WATERSHED-SCALE FUNDING SOLUTION

by Tim Wigington, Stephanie Tatge, Xia Vivian Zhou, Nick Osman & Danielle Dumont
The Freshwater Trust (Portland, OR)

Introduction

Improving Waterways

The United States has made significant progress towards restoring and improving water resources on some fronts since the passage of the Clean Water Act in 1972. However, despite the trillions of dollars invested over recent decades, more than half of America’s waterways still do not meet water quality standards. On top of this, growing climate pressures are exacerbating flood, drought, and fire risks in almost every watershed. In short, we haven’t achieved our goals, and it’s getting harder to do so with each passing year.

Current Funding System — Not Delivering Results at Scale

Funding

Technology is now available to identify, target, and implement conservation actions at the scale necessary to secure resilient watersheds. The challenge has become how to quickly organize and deploy the trillions of new dollars available to produce the best environmental outcomes. In 2022, President Biden signed the Inflation Reduction Act (IRA) into law, just months after also enacting the Bipartisan Infrastructure Law (BIL). The tens of billions in new funding from both laws provide a significant opportunity to build critical natural-resource-related infrastructure and implement climate-smart agriculture initiatives on a national scale. However, adding new money is just the first half to getting better results.

Challenges

Currently, most funding from government programs is disbursed through process-heavy, technical, and lengthy project-by-project grant or loan programs. Many of these programs have “match” funding requirements that make it difficult for partners to leverage together multiple programs, even if they have similar objectives. The potential to use multiple programs to reinforce funding is also splintered, with each program focused on a sliver of the problem. On the project side, the long, uncertain, and costly application cycles associated with these programs often deter landowners with key lands and projects from participating. Because each program is structured differently and focuses on a different part of the problem, it is difficult to determine what environmental outcomes have been produced and how the outcomes add up compared to watershed needs.

Watershed-Scale Investment Solution — Proposed USDA Action

Quantifying Outcomes

The Freshwater Trust (TFT) proposes a solution that helps to reassemble these currently disparate efforts into a collective watershed-wide investment approach. With watershed analytics, agencies and practitioners can effectively quantify the “outcomes” of projects using measurements such as: gallons of water saved; tons of carbon sequestered; or pounds of excess nutrients avoided. These measurements make it possible to coordinate investment of otherwise splintered public funds toward priority projects in the watershed that produce outcomes most cost-effectively. *See* https://www.thefreshwatertrust.org/combining-technology-and-financial-tools-in-new-ways-to-solve-tough-water-problems/.

Multiple Benefits

For example, if one government funding program needs greenhouse gas emission reductions, another needs nutrient reductions, another needs water quantity savings, and a final program wants to support underserved rural community resilience, funding from all programs can be combined to support an irrigation modernization project because this type of project produces all those desired outcomes.

USDA Funding

Making it possible for multiple agencies to participate in this type of coordinated watershed funding approach will require some targeted policy changes. One of those specific changes — which is the focus of this article — relates to the IRA funding added to US Department of Agriculture (USDA) conservation programs. The IRA instructed USDA to prioritize $19 billion in new funding to “climate-smart” projects that directly improve soil carbon, reduce nitrogen losses, or sequester carbon dioxide (CO_2), methane (CH_4), or nitrous oxide (N_2O) emissions (collectively greenhouse gases, or GHGs). To be eligible for this priority IRA funding, projects must use one or more climate-smart conservation practices from the USDA Natural Resources Conservation Service’s (NRCS) Climate-Smart Agriculture and Forestry Mitigation Activities List (CSAF List) (NRCS, 2023). *See* https://www.nrcs.usda.gov/conservation-basics/natural-resource-concerns/climate/climate-smart-mitigation-activities.

Smart Irrigation

Solution

While the CSAF List includes many important practices, it does not currently include any related to irrigation modernization except for a small carveout limited to rice fields. Adding this practice class to the CSAF List has the potential to mobilize IRA funding to include a set of practices that *simultaneously* reduce GHG emissions, improve water quality, and support Western farmers' and water managers' initiatives to sustain their operations through long-term drought. This addition alone will not solve watershed-scale funding and implementation challenges, but it will be a big step forward in terms of broadening the potential for IRA funds to deliver impact in the Western United States. This article summarizes the technical case for adding this group of irrigation modernization practices to the CSAF List, and potentially offers a template for making similar cases to NRCS to add additional multi-benefit practices to the CSAF List.

The Case for Adding Irrigation Modernization to the Climate-Smart List

Definition

TFT defines "irrigation modernization" as the *improvement of water use efficiency via pressurization of irrigation systems on currently irrigated agricultural lands,* through the adoption of NRCS practices for irrigation pipeline (430), microirrigation systems (441), sprinkler systems (442), and irrigation water management (449) (NRCS, 2020a, 2020b, 2020c, 2021). This definition does not include irrigating previously non-irrigated lands, changing water management practices while maintaining unpressurized (flood) irrigation systems, or installing an unpressurized subirrigation system. Irrigation modernization does include converting unpressurized irrigation to pressurized sprinkler or microirrigation, as well as upgrading already pressurized systems from sprinklers to microirrigation.

Emission Reductions

This article lays out the strong evidence showing how irrigation modernization practices can reduce N_2O and CH_4 emissions similar to practices already on the CSAF List. As seen in Figure 1, just under half (49%) of agriculture's GHG emissions in 2018 were N_2O and CH_4 emissions from cropland soils and grazing lands (United States Department of Agriculture et al., 2022). Analysis by TFT details the scientifically robust, existing methods available to quantify the GHG emission reduction benefits generated by these irrigation modernization practices, utilizing some of the same methods that support practices already on the CSAF List. The analysis also demonstrates how irrigation modernization facilitates other climate-smart practices.

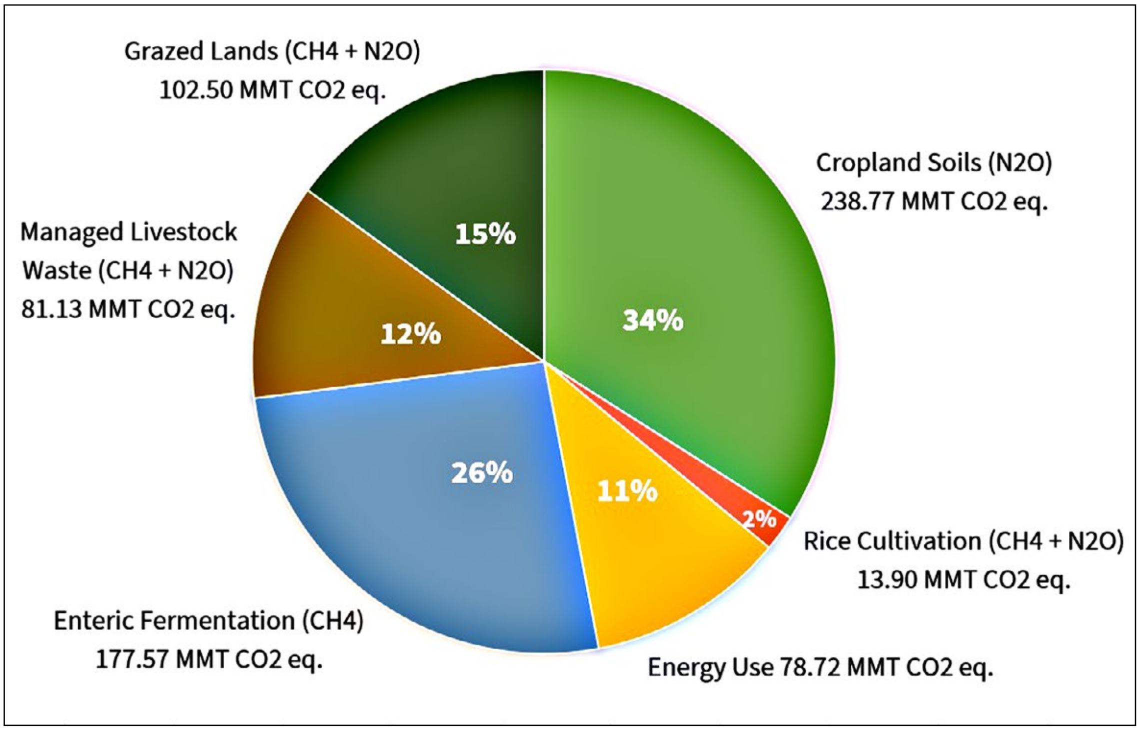


Figure 1. Agricultural sources of greenhouse gas in 2018. MMT CO2 eq. means million metric tons of carbon dioxide equivalent. Adapted from US Agriculture and Forestry Greenhouse Gas Inventory 1990-2018: Technical Bulletin 1957 (USDA et al., 2022).

Smart Irrigation

Adding irrigation modernization practices will provide NRCS, communities, and partners with another pathway to secure meaningful GHG emission reductions while also supporting producers as they navigate unprecedented water scarcity challenges driven by climate change. This opportunity is greatest in the Western states, where 71% of our nation's irrigated agricultural lands are located. Nationwide, at least one-third of irrigated agricultural lands still use unpressurized irrigation methods (McGee, 2016), so adding this practice could be utilized by a lot of producers.

Flood Irrigation

Flood irrigators can benefit from practices already on the CSAF List. Practices that could reduce GHG emissions or sequester carbon in flood irrigated acres include: Field Borders (386); Nutrient Management (590); Pasture and Hay Planting (512); and Range Planting (550). Adding irrigation modernization to the CSAF List is not intended to imply that flood irrigators should choose irrigation modernization over the other practices on the CSAF List. Rather, this analysis is meant to illustrate that converting gravity systems to pressurized pipe systems can also quantifiably decrease GHG emissions.

Multiple Factors

TFT recognizes that GHG reduction benefits are just one of many factors that need to be considered when making water management decisions. Other factors that need to be considered in addition to GHG benefits include crop yield, affordability, practicality, other benefits to the environment, and the economic bottom line. Accordingly, irrigation modernization practices should be included as options in the CSAF toolkit in addition to those already available.

Modelling Conservation Practice Impacts

Practices

The USDA report *Quantifying Greenhouse Gas Fluxes in Agriculture and Forestry: Methods for Entity-Scale Inventory (Methods for Entity-Scale Inventory)* provides the scientific foundation for the NRCS conservation practices included on the CSAF List (Eve et al., 2014). The CSAF List states that "listed practices have quantifiable carbon sequestration and/or GHG reduction methodologies described in COMET-Planner." NRCS Conservation Practices and GHG quantification methods used in the COMET-Planner modeling tool are closely aligned with those identified in the USDA's *Methods for Entity-Scale Inventory.* In the 2014 report, USDA: (a) designates irrigation as one of ten "management practices impacting GHG emissions from croplands and grazing lands;" (b) outlines evidence in the literature for reductions in soil emissions resulting from irrigation modernization (described below); and (c) provides scientifically defensible methods for the quantification of changes in N_2O and CH_4 with implementation of irrigation and water management practices.

Quantifying Benefits

Unfortunately, the 2014 USDA report did not explicitly include any GHG quantification methods for irrigation modernization practices on croplands or grazing lands. In recent years, quantification methods have been developed for irrigation modernization to fill this gap, particularly the Daily Century (DayCent) and Denitrification-Decomposition (DNDC) models. These methods provide scientifically defensible options for quantifying changes in emissions from irrigation modernization and have been used in multiple studies to evaluate changes in N_2O and CH_4 emissions (described below). With these advances, it's now possible to close the loop, and fully quantify the GHG-related benefits from irrigation modernization.

The CSAF List also states that "conservation practices that facilitate the management or the function of a CSAF mitigation activity but may not achieve the desired effects on their own (and may not have a quantifiable benefit) may be planned as applicable." These practices can be supported by NRCS through Climate-Smart programs when they are implemented in conjunction with CSAF mitigation activities. While Conservation Practices 430, 441, 442, and 449 have their own GHG reduction benefits to support inclusion on the CSAF List as stand-alone practices, they also qualify as significant "facilitating practices" for multiple, currently listed CSAF mitigation activities, including nitrogen management and reduced tillage (described below).

Evidence of Lower GHG Emissions from Irrigation Modernization

Flood Irrigation

Unpressurized irrigation methods use a significant volume of water that is applied to an entire field every few days. This practice results in greater losses to seepage below the root zone compared to pressurized sprinkler and microirrigation systems (Ross et al., 1997). Pressurized, more frequent, and targeted irrigation systems reduce GHG emissions through more consistent and direct watering of crop roots. This approach moderates the two major processes that drive GHG emissions in unpressurized systems: (1) soil wetting and drying cycles that increase N_2O emissions; and (2) soil anoxic conditions that increase CH_4 emissions. Pressurized and managed irrigation systems also improve uptake of nitrogen by plants (further reducing N_2O) and decrease nitrogen runoff and leaching that cause indirect N_2O emissions.

Smart Irrigation

USDA's 2014 *Methods for Entity-Scale Inventory* summarizes research and science that drive GHG emissions under various forms of irrigation. USDA provides reasoning and evidence for higher N_2O (and in some cases CH_4) emissions in unpressurized systems compared to pressurized systems. Pressurized systems are used to apply lower volumes of water more consistently to root zones.

Irrigation Impacts

Key statements from *Methods for Entity-Scale Inventory* (beginning on p. 3-19) include:

Unpressurized flood: "Flood irrigation involves flooding the entire field with water. Under continuously flooded conditions, soils are highly anoxic, thus facilitating high methanogenesis and denitrification rates (Mosier et al., 2006)."

Unpressurized furrow: "The impact of furrow irrigation on GHG emissions depends on how often and the extent to which furrows are filled with water. Wetting and drying cycles are likely to emit large pulses of NO and N_2O (Davidson, 1992)."

Pressurized sprinkler: "During and shortly after [sprinkler] irrigation events, soil may become saturated and emit pulses of N_2O, but because the soil is not continuously saturated, N_2O emissions are expected to be lower compared with surface [furrow] irrigation (Nelson & Terry, 1996)."

Pressurized surface drip: "The impacts of surface drip irrigation on GHG fluxes are expected to be similar to those of sprinkler systems, ...there is early evidence that both surface and subsurface drip irrigation leads to less emissions of CH_4 and N_2O (Kallenbach et al., 2010; Kennedy et al., 2013)."

Pressurized subsurface drip: "Soil water content has less temporal variation with subsurface drip irrigation compared with sprinkler and surface systems, so pulses of N_2O...emissions are also expected to be of smaller magnitude (Kallenbach et al., 2010). Similarly, subsurface drip irrigation/fertigation [i.e., the application of fertilizer solutions via irrigation] of high-value crops, such as tomatoes, has been shown to reduce N_2O emissions compared with furrow irrigation (Kennedy et al., 2013)."

NITROUS OXIDE IRRIGATION EMISSIONS & RESEARCH

Evidence

In addition to the USDA report, TFT gathered independent evidence on N_2O emissions and irrigation practices. For example, Sapkota et al. (2020) reviewed empirical field studies related to irrigation modernization and GHG emissions in a meta-analysis. They concluded that: (1) in arid regions, high-intensity irrigation methods (defined as high volume and more intermittent applications) showed the greatest N_2O production; and (2) the maximum N_2O flux from unpressurized irrigated fields was higher than the maximum on pressurized irrigated fields.

Studies

One caveat to this meta-analysis is that it was difficult to isolate the impacts of irrigation modernization from changes to fertilizer application, cover cropping, and tillage practices — which often varied between the studies' treatments. Therefore, TFT isolated the studies reviewed by USDA and Sapkota that align with the irrigation modernization practices that were excluded from the CSAF List. These studies and their results are summarized in Table 1 (see below) along with additional relevant studies not included in their review.

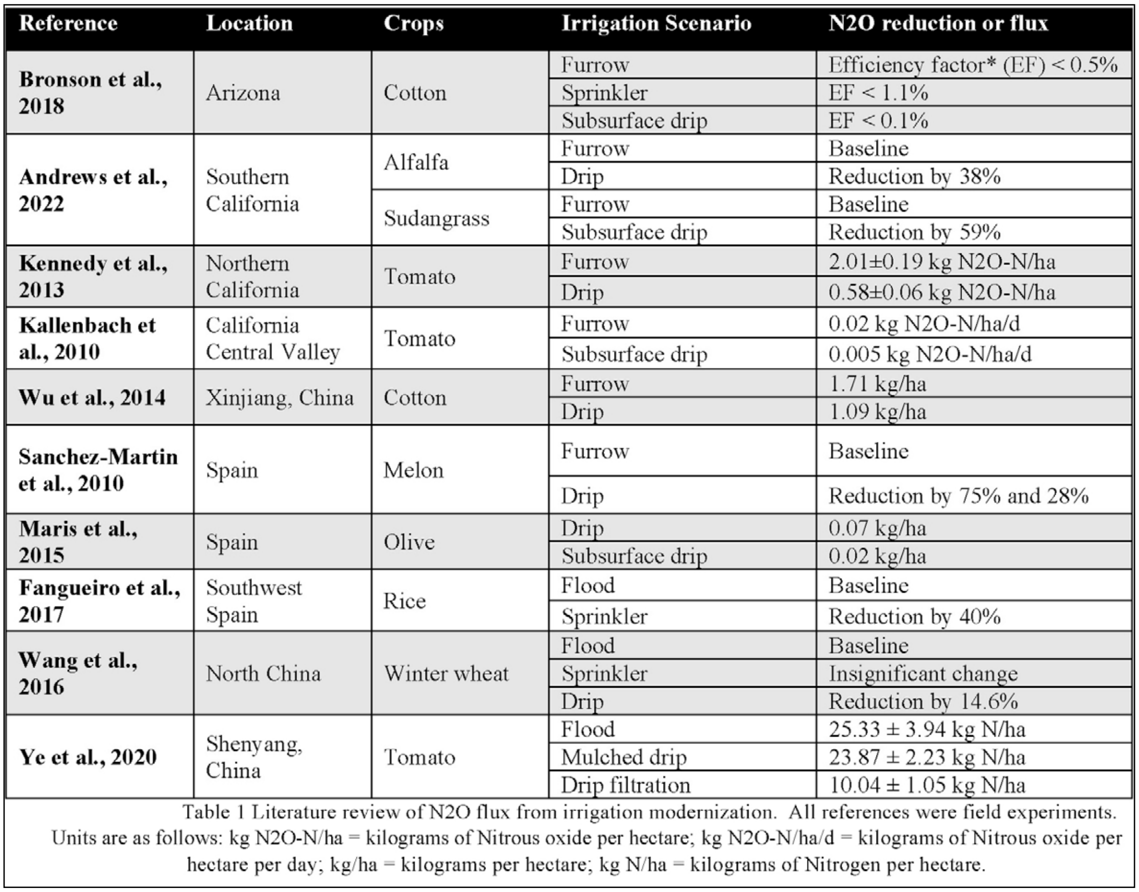
Results

The field study results summarized in Table 1 consistently show reduced N_2O emissions from high-efficiency pressurized irrigation systems when compared to unpressurized systems. The most relevant studies show where irrigation was varied on non-rice crops grown in arid or semi-arid regions of the US, including hay and alfalfa in southern California (Andrews et al., 2022); cotton in Arizona (Bronson et al., 2018), and tomatoes grown in northern California (Kennedy et al., 2013) and California's Central Valley (Kallenbach et al., 2010). In each case, N_2O emissions were 25% to 75% lower in the pressurized systems when compared to unpressurized systems. Similar results were found in studies of cropping systems in arid and semi-arid regions outside the US, including in Spain and northern China.

Irrigation Types

Most studies compared unpressurized systems to high-efficiency systems. TFT found only three studies that compared N_2O emissions between unpressurized and sprinkler systems. Of these three, Fangueiro et al. (2017) saw 40% lower N_2O emissions on sprinkler irrigation fields relative to flooding. The other two studies saw no significant difference in N_2O from sprinklers relative to unpressurized methods (Bronson et al., 2018; Wang et al., 2016). While sprinkler irrigation conversions were less conclusive with respect to N_2O reductions, this practice does provide other GHG reduction benefits as outlined in the CH_4 subsection below.

Smart Irrigation



Reference	Location	Crops	Irrigation Scenario	N2O reduction or flux
Bronson et al., 2018	Arizona	Cotton	Furrow	Efficiency factor* (EF) < 0.5%
			Sprinkler	EF < 1.1%
			Subsurface drip	EF < 0.1%
Andrews et al., 2022	Southern California	Alfalfa	Furrow	Baseline
			Drip	Reduction by 38%
		Sudangrass	Furrow	Baseline
			Subsurface drip	Reduction by 59%
Kennedy et al., 2013	Northern California	Tomato	Furrow	2.01±0.19 kg N2O-N/ha
			Drip	0.58±0.06 kg N2O-N/ha
Kallenbach et al., 2010	California Central Valley	Tomato	Furrow	0.02 kg N2O-N/ha/d
			Subsurface drip	0.005 kg N2O-N/ha/d
Wu et al., 2014	Xinjiang, China	Cotton	Furrow	1.71 kg/ha
			Drip	1.09 kg/ha
Sanchez-Martin et al., 2010	Spain	Melon	Furrow	Baseline
			Drip	Reduction by 75% and 28%
Maris et al., 2015	Spain	Olive	Drip	0.07 kg/ha
			Subsurface drip	0.02 kg/ha
Fangueiro et al., 2017	Southwest Spain	Rice	Flood	Baseline
			Sprinkler	Reduction by 40%
Wang et al., 2016	North China	Winter wheat	Flood	Baseline
			Sprinkler	Insignificant change
			Drip	Reduction by 14.6%
Ye et al., 2020	Shenyang, China	Tomato	Flood	25.33 ± 3.94 kg N/ha
			Mulched drip	23.87 ± 2.23 kg N/ha
			Drip filtration	10.04 ± 1.05 kg N/ha

Table 1 Literature review of N2O flux from irrigation modernization. All references were field experiments. Units are as follows: kg N2O-N/ha = kilograms of Nitrous oxide per hectare; kg N2O-N/ha/d = kilograms of Nitrous oxide per hectare per day; kg/ha = kilograms per hectare; kg N/ha = kilograms of Nitrogen per hectare.

* Efficiency factor (EF) is the percentage of applied nitrogen fertilizer emitted as N_2O and can therefore be used to standardize application rates. Since the application rates varied under the treatments, it's likely that the modernized irrigation systems produced lower absolute N_2O emissions than the furrow baseline, but these values were not provided in the study.

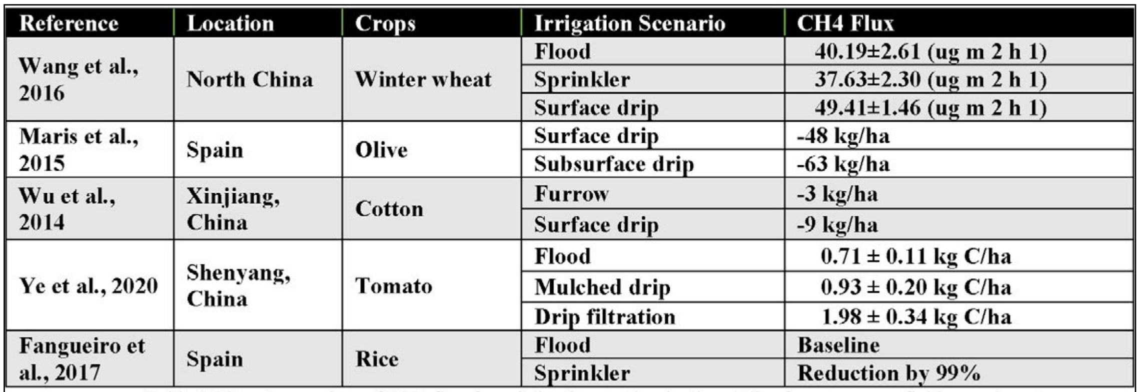
METHANE IRRIGATION EMISSIONS & RESEARCH

Saturation Variations

Irrigation management systems affect oxygen availability in soil, and methanogenic microbes are most competitive in anoxic conditions; therefore, irrigation efficiency is well correlated to methane emission reductions (Nguyen et al., 2015). Flood irrigation systems saturate soils deeply and lower soil oxygen levels, causing anaerobic conditions that favor methanogens (Eagle & Olander, 2012) and ultimately produce CH_4 emissions (Eve et al., 2014; Nelson & Terry, 1996). Pressurized systems irrigate more precisely and uniformly distribute water to root zones, which can interrupt anerobic microbial processes such as methanogenesis. High-efficiency systems lead to even fewer emissions of CH_4 than sprinkler and surface irrigations because drip irrigation reduces evaporative loss and avoids full saturation of soil pores (Del Grosso et al., 2000; Kallenbach et al., 2010; Kennedy et al., 2013).

Results

Table 2 summarizes multiple published studies that showed methane reductions from irrigation modernization on agricultural fields without negative yield effects (Nie et al., 2023; Sapkota et al., 2020; Zschornack et al., 2016). A three-year rice study in southwest Spain found that sprinkler irrigation decreased CH_4 emission by 99% relative to flood irrigation (Fangueiro et al., 2017). A winter wheat study in a semi-arid region of northern China showed that CH_4 uptake in high-efficiency irrigation systems increased more than 20% compared to flood irrigation fields due to the lower frequency wetting/drying cycles, lower soil moisture, improved oxygen diffusion, and increased CH_4 oxidation (Wang et al., 2016). It is hypothesized in the literature that under the aerobic soil conditions common in modernized irrigation methods, a high redox potential prevents the formation of CH_4, or permits its oxidation by methanotrophic bacteria (Aulakh et al., 2001).



Reference	Location	Crops	Irrigation Scenario	CH4 Flux
Wang et al., 2016	North China	Winter wheat	Flood	40.19±2.61 (ug m 2 h 1)
			Sprinkler	37.63±2.30 (ug m 2 h 1)
			Surface drip	49.41±1.46 (ug m 2 h 1)
Maris et al., 2015	Spain	Olive	Surface drip	-48 kg/ha
			Subsurface drip	-63 kg/ha
Wu et al., 2014	Xinjiang, China	Cotton	Furrow	-3 kg/ha
			Surface drip	-9 kg/ha
Ye et al., 2020	Shenyang, China	Tomato	Flood	0.71 ± 0.11 kg C/ha
			Mulched drip	0.93 ± 0.20 kg C/ha
			Drip filtration	1.98 ± 0.34 kg C/ha
Fangueiro et al., 2017	Spain	Rice	Flood	Baseline
			Sprinkler	Reduction by 99%

Table 2 Literature review of CH4 flux from irrigation modernization. All references were field experiments.
Units: ug m 2 h 1= micrograms per square meter per hour

GHG Quantification Methods for Irrigation Modernization

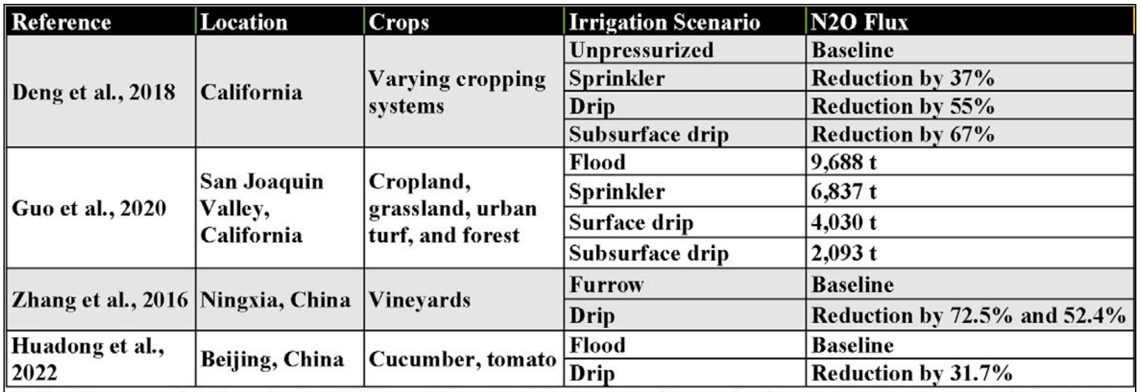
Models

Two biogeochemical models — **Den**itrification-**Dec**omposition (DNDC) and Daily Century (DayCent) — are the most widely used models to quantify GHG emissions from agricultural soils (Institute for Study of Earth, Oceans and Space, 2012; Li et al., 2005; Parton et al., 2001; Wang et al., 2021). Both DNDC and DayCent are simulation tools to predict soil fluxes of N_2O, CH_4, and CO_2 with various farm management practices, such as irrigation, cropping, tillage, fertilization, and grazing (Del Grosso et al., 2000; Deng et al., 2018, 2020; Institute for Study of Earth, Oceans and Space, 2012; Necpálová et al., 2015; Parton et al., 2001).

Results

Previous studies have used the DNDC model to evaluate the impacts of conversion from unpressurized to pressurized irrigation on N_2O and CH_4 emissions, which are summarized in Table 3. A study using the DNDC model simulated cropping systems in California from 2001 to 2010 found that drip irrigation is predicted to reduce N_2O emissions by 55-67% relative to unpressurized irrigation (Deng et al., 2018). In another study, the DNDC model was used to simulate soil fluxes for cropland in California's San Joaquin Valley from 2011 to 2013, and the results indicate that sprinkler, surface drip, and subsurface drip irrigation systems are predicted to decrease N_2O emission by 29%, 58%, and 78%, respectively, relative to unpressurized irrigation (Guo et al., 2020).

Outside the US, the DNDC model has been used to assess effects of irrigation modernization on soil fluxes in China, including a study for vineyards in Ningxia that indicated drip irrigation is predicted to reduce N_2O emission by 72.5% in 2012 and by 52.4% in 2013, relative to unpressurized irrigation (Zhang et al., 2016). DNDC model simulations for cucumber and tomato production in Beijing, China during 2017 and 2018 indicate that drip irrigation is predicted to reduce N_2O emissions by 31.7%, relative to unpressurized irrigation (Huadong et al., 2022).



Reference	Location	Crops	Irrigation Scenario	N2O Flux
Deng et al., 2018	California	Varying cropping systems	Unpressurized	Baseline
			Sprinkler	Reduction by 37%
			Drip	Reduction by 55%
			Subsurface drip	Reduction by 67%
Guo et al., 2020	San Joaquin Valley, California	Cropland, grassland, urban turf, and forest	Flood	9,688 t
			Sprinkler	6,837 t
			Surface drip	4,030 t
			Subsurface drip	2,093 t
Zhang et al., 2016	Ningxia, China	Vineyards	Furrow	Baseline
			Drip	Reduction by 72.5% and 52.4%
Huadong et al., 2022	Beijing, China	Cucumber, tomato	Flood	Baseline
			Drip	Reduction by 31.7%

Table 3 Summary of studies using the DNDC model to evaluate the impacts of conversion from unpressurized to pressurized irrigation on N2O and CH4 emissions.

Inputs

DayCent does not use specific irrigation types as inputs, such as flood, sprinkler, and drip, but it does allow other relevant inputs that approximate irrigation modernization, such as irrigation intensity (low, medium, or high), volume, frequency, and timing (Olander et al., 2011). DayCent has been used widely for simulating N_2O emissions from agricultural soils from various irrigation, cropping systems, and fertilization (Del Grosso et al., 2005; Eve et al., 2014).

Accuracy

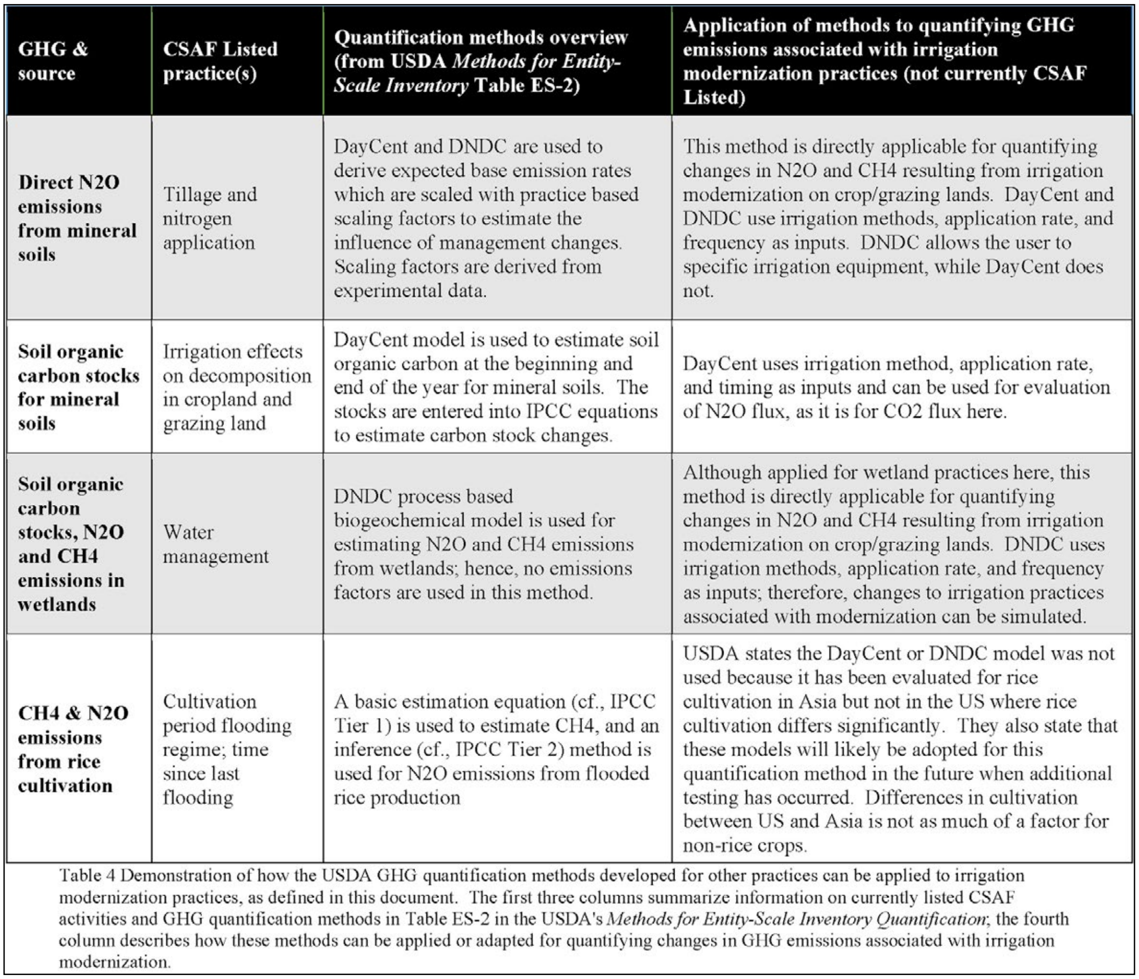
Recent research calibrated and validated both DayCent and DNDC models using measured data from a turfgrass field experiment with medium and low irrigation in Kansas (Hong et al., 2023). The study concluded that DayCent model results were accurate ranging from -54% to 14% and therefore *adequately* estimated N_2O emission reductions from soils with low and medium irrigation and N-fertilization treatments, while DNDC model results ranged from -24% to -85% and therefore *underestimated* N_2O emission reductions from the tested practices (Hong et al., 2023). This underestimation by DNDC could be addressed by incorporating empirical data into quantification methods for irrigation modernization.

Empirical Data

The DayCent or DNDC methods can be used at the farm or regional scale throughout the US to simulate irrigation modernization practices. Irrigation method, application, and frequency are key inputs to both models, which account for changes in soil microbial activity and plant growth rates that impact net GHG flux. These process-based models facilitate scaling and account for spatial heterogeneity at the farm scale, while available empirical data can be used to quantify and address model uncertainty. Where field-based measurement validation is lacking for the N_2O and CH_4 estimates from process-based models, empirical data are available (or can be gathered) to produce "emissions factors" for simpler or more accurate quantification methods.

Quantification Methods

The 2014 USDA *Methods for Entity-Scale Inventory* already describe DNDC and DayCent as quantification methods for multiple practices included on the CSAF List (including forms of irrigation and water management). These existing quantification frameworks used in COMET-Planner can also be applied to irrigation modernization practices. Table 4 describes how quantification methods used for other CSAF Listed management practices — particularly those that involve irrigation or water management — can be easily adapted or applied to irrigation modernization.



GHG & source	CSAF Listed practice(s)	Quantification methods overview (from USDA *Methods for Entity-Scale Inventory* Table ES-2)	Application of methods to quantifying GHG emissions associated with irrigation modernization practices (not currently CSAF Listed)
Direct N2O emissions from mineral soils	Tillage and nitrogen application	DayCent and DNDC are used to derive expected base emission rates which are scaled with practice based scaling factors to estimate the influence of management changes. Scaling factors are derived from experimental data.	This method is directly applicable for quantifying changes in N2O and CH4 resulting from irrigation modernization on crop/grazing lands. DayCent and DNDC use irrigation methods, application rate, and frequency as inputs. DNDC allows the user to specific irrigation equipment, while DayCent does not.
Soil organic carbon stocks for mineral soils	Irrigation effects on decomposition in cropland and grazing land	DayCent model is used to estimate soil organic carbon at the beginning and end of the year for mineral soils. The stocks are entered into IPCC equations to estimate carbon stock changes.	DayCent uses irrigation method, application rate, and timing as inputs and can be used for evaluation of N2O flux, as it is for CO2 flux here.
Soil organic carbon stocks, N2O and CH4 emissions in wetlands	Water management	DNDC process based biogeochemical model is used for estimating N2O and CH4 emissions from wetlands; hence, no emissions factors are used in this method.	Although applied for wetland practices here, this method is directly applicable for quantifying changes in N2O and CH4 resulting from irrigation modernization on crop/grazing lands. DNDC uses irrigation methods, application rate, and frequency as inputs; therefore, changes to irrigation practices associated with modernization can be simulated.
CH4 & N2O emissions from rice cultivation	Cultivation period flooding regime; time since last flooding	A basic estimation equation (cf., IPCC Tier 1) is used to estimate CH4, and an inference (cf., IPCC Tier 2) method is used for N2O emissions from flooded rice production	USDA states the DayCent or DNDC model was not used because it has been evaluated for rice cultivation in Asia but not in the US where rice cultivation differs significantly. They also state that these models will likely be adopted for this quantification method in the future when additional testing has occurred. Differences in cultivation between US and Asia is not as much of a factor for non-rice crops.

Table 4 Demonstration of how the USDA GHG quantification methods developed for other practices can be applied to irrigation modernization practices, as defined in this document. The first three columns summarize information on currently listed CSAF activities and GHG quantification methods in Table ES-2 in the USDA's *Methods for Entity-Scale Inventory Quantification*; the fourth column describes how these methods can be applied or adapted for quantifying changes in GHG emissions associated with irrigation modernization.

How Irrigation Modernization Facilitates Climate-Smart Activities

The CSAF List includes the following direction: "In addition to the designated CSAF mitigation activities listed, conservation practices that facilitate the management or the function of a CSAF mitigation activity but may not achieve the desired effects on their own (and may not have a quantifiable benefit) may be planned as applicable." The sections above demonstrate that irrigation modernization does "achieve the desired effects" on its own, and clearly has substantial quantifiable benefits. In addition, irrigation modernization has also been shown to facilitate other CSAF mitigation activities.

Fertilizer Management

For example, in the *Methods for Entity-Scale Inventory,* USDA states that "optimizing other practices — including tillage and the management of soil pH, pests, irrigation, drainage, and other factors — will tend to increase nitrogen fertilizer uptake by the crop and therefore reduce N_2O emissions." (Chapter 3.2.1.2; page 3-16). Indeed, fertilizer management is a suite of agricultural practices that strongly control soil mineral nitrogen availability for the nitrification and denitrification process in which N_2O emissions are produced in soils (Abbasi & Adams, 2000). N_2O emission is positively correlated with nitrogen fertilizer application rates, which in turn are affected by irrigation efficiency and the potential for fertigation (Akiyama et al., 2004).

Efficient Irrigation

A recent paper analyzed the extent to which the adoption of efficient irrigation practices mediated the adoption of climate-smart soil health practices in diverse cropping systems in California. The analysis demonstrated that pressurized irrigation systems are an especially important farm operation characteristic for the adoption of many nitrogen management and soil health practices (Rudnick et al., 2021). This is particularly relevant to the CSAF List because almost half of the eligible practices (14 out of 32 non-provisional practices) fall under the categories of soil health or nitrogen management.

Soil Health

This relationship is further exemplified by a University of Colorado Boulder report that claims irrigation modernization provides Colorado farmers with the ability to adopt zero tillage and reduced tillage practices. They state that sprinkler and microirrigation systems do not compact the soil like many flood irrigation systems and, therefore, "expand options for zero-tillage and safeguard soil health" (UC Boulder, 2020). This means that adding irrigation modernization to the CSAF List of eligible practices is likely to facilitate the adoption of additional CSAF-eligible practices by the same producer, multiplying GHG-emission reduction benefits while investing in a producer's operation and creating other co-benefits including water quality improvement and soil health.

Flood Irrigation Benefits

While flood irrigation may lead to GHG emissions, it may provide other benefits in some cases, such as wildlife habitat, ecosystem function, hydrologic benefits such as aquifer recharge or stream baseflow, and other societal benefits. Alternative CSAF practices can be adopted to maintain those benefits while investing in the enhancement of an operation. Ranchers and farmers will be the experts on their own operations and will need to carefully consider all these elements when making specific implementation choices.

Conclusion

Impact

The upcoming strategic investment of Farm Bill funds through the IRA represents an unprecedented opportunity to increase the pace and scale of conservation investment and to enable multiple funders to leverage their investments together more easily at the watershed scale. Adding irrigation modernization practices to the CSAF List will help secure GHG reduction benefits, while also positioning many rural communities for long-term water resilience from the impacts of climate change, enhancing domestic food supply, and supporting a healthy environment for the future. These practices not only help address the causes of climate change but can also be implemented in a way that helps mitigate the severe water-related impacts being experienced in the Western United States.

For Additional Information:

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The Freshwater Trust, protects and restores freshwater ecosystems using science, technology, and incentive-based solutions. The 40-year-old nonprofit is the largest restoration-focused organization in the Pacific Northwest and the second largest conservation group based in Oregon. The Freshwater Trust has pioneered a "Quantified Conservation" approach using data and technology to ensure every restoration action taken translates to a positive outcome.

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