

Review

Soil Management Practices to Mitigate Nitrous Oxide Emissions and Inform Emission Factors in Arid Irrigated Specialty Crop Systems

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Abstract: Greenhouse gas (GHG) emissions from arid irrigated agricultural soil in California have been predicted to represent 8% of the state's total GHG emissions. Although specialty crops compose the majority of the state's crops in both economic value and land area, the portion of GHG emissions contributed by them is still highly uncertain. Current and emerging soil management practices affect the mitigation of those emissions. Herein, we review the scientific literature on the impact of soil management practices in California specialty crop systems on GHG nitrous oxide emissions. As such studies from most major specialty crop systems in California are limited, we focus on two annual and two perennial crops with the most data from the state: tomato, lettuce, wine grapes and almond. Nitrous oxide emission factors were developed and compared to Intergovernmental Panel on Climate Change (IPCC) emission factors, and state-wide emissions for these four crops were calculated for specific soil management practices. Dependent on crop systems and specific management practices, the emission factors developed in this study were either higher, lower or comparable to IPCC emission factors. Uncertainties caused by low gas sampling frequency in these studies were identified and discussed. These uncertainties can be remediated by robust and standardized estimates of nitrous oxide emissions from changes in soil management practices in California specialty crop systems. Promising practices to reduce nitrous oxide emissions and meet crop production goals, pertinent gaps in knowledge on this topic and limitations of this approach are discussed.

Keywords: soil processes; management practices; mitigation; specialty crops; California; emission factor

1. Introduction

Irrigated agriculture, producing nearly 40% of food and agricultural commodities globally, is recognized as a source of considerable greenhouse gas (GHG) emissions [1,2]. In California, irrigated agriculture, which is all in arid regions, contributes to 8% of the state's total GHG emissions and 7% of the total U.S. agricultural GHG emissions, making it the nation's largest agricultural emitter [3,4].



That the GHG nitrous oxide (N₂O), with a global warming potential 298 times greater than carbon dioxide (CO₂), is primarily emitted by agriculture when soil processes respond to management practices is well known [5]. Less certain are the nuanced management practices that will reduce N₂O emissions from agriculture to aid in climate change mitigation. Although specialty crops compose the majority of the state's crops in both economic value and land area, the contribution of specialty crop systems to the state's total GHG is also highly uncertain due to the diverse range of regional microclimates, soil types and crops, and complex rotation schedules currently in use [3,6–8]. Many specialty crops still lack empirical data demonstrating their role in N₂O emissions. Thus, ongoing efforts (e.g., CDFA Healthy Soils Initiative, research supported by Specialty Crop Block Grants and other programs) support the identification of GHG mitigation opportunities in California agriculture [9–11]. To understand and prioritize mitigation opportunities, it is important to understand the magnitude of N₂O emissions in these dominant cropping systems, the mechanisms for emissions and the role that conservation practices can play in reducing those emissions.

Nitrous oxide emissions derive from soil management practices like fertilization, irrigation and tillage [4,6]. These management practices, as well as climate, can influence factors that elicit high spatio-temporal variability in N₂O emissions (Figure 1). These factors include fluctuations in water content, oxygen levels, pH and the availability of carbon (C) and nitrogen (N) [12–15]. Biological and chemical processes that produce N₂O include ammonia oxidation pathways (i.e., nitrifier nitrification, nitrifier denitrification and nitrification coupled denitrification), heterotrophic denitrification and abiotic chemodenitrification [15,16]. Current knowledge on the mechanistic understanding of soil N₂O production pathways and their controls has been reviewed by Zhu-Barker and Steenwerth [17].



Figure 1. Soil management practices and factors affecting N_2O emissions from soils. Blue arrows represent the relationships between soil factors and N_2O production pathways. Black arrows represent the relationships between soil management practices and soil factors that can be directly changed by these practices.

California is the nation's largest agricultural producing state, with USD 46B in cash receipts [18], and has the largest specialty crop acreage [6,7]. It is the nation's only commercial producer for many specialty crops, including almonds, raisins, walnuts, pistachios, olives, prunes and other stone fruits [19]. For other specialty crops like wine grapes, strawberries, leaf lettuce, garlic, broccoli and Brussels sprouts, California's share approaches or exceeds 90% of U.S. production [20]. Despite the diversity of specialty crops grown in the state, however, a small number of crops (e.g., grapes, almonds, strawberries, lettuce, walnuts and tomatoes) account for most of the specialty crop economic value and land area in California. California farmland in orchard and vineyards is approximately 34% of the state farmland [21].

Woody perennials have occupied an increasingly larger proportion of the state's landscape over the past few decades, especially given the increasing market value of these crops. This trend suggests that woody perennials play an important role in N₂O emissions from California. However, detailed and accurate inventories on N₂O emissions from these systems are rare and difficult to quantify, in part because of the spatial complexity of perennial crop systems [22,23]. Studies that have examined N₂O emissions from woody perennials and the effects of specific management have occurred in wine grapes [24–30] and almonds [31–37]. Only one study on N₂O emissions from walnuts is available [38]. Other specialty crop systems that lack any characterization of N₂O emissions in response to management practices include citrus, raisins, table grapes, cole crops, stone fruits and strawberries, whereas other crops like lettuce and tomatoes have been examined more closely [39–43].

Given the dearth of empirical data on N₂O emissions from the state's agricultural systems, emission factors represent one means to broadly quantify and compare impacts of soil management practices on GHG emissions. Nitrous oxide emission factors (EFs) are defined as the amount of N₂O-N emitted as a percentage of the applied N based on empirical measurements. EFs provide an alternative means to assess N₂O emissions associated with specific soil management practices. The outcome of process-based models like DayCent [44] can also be used to calculate EFs of N fertilizer under specific management practices, but this approach is limited by lack of available empirical data from many specialty crop systems to parameterize and calibrate the model [45–47].

Here, we review empirical studies of N_2O emissions from California's specialty crops, focusing on those that quantify annual emissions. First, we summarize management practices that influence N_2O emissions from specialty crop systems, including fertilization, irrigation, cover crops and tillage, and then characterize the implementation of these practices within tomatoes, lettuce, grapes and almonds. These empirical studies will be leveraged to calculate EFs based on practice and crop, and the resultant EFs will be utilized to estimate statewide emissions based on the respective crop's production area in the state. A complete assessment of the major specialty crops, management practices and associated N_2O emissions based on empirical data is not yet possible. As such, we identify limitations of this approach and gaps where further efforts will bolster the capacity to determine practice-based emissions from the state's specialty crops.

2. Materials and Methods

2.1. Literature Review—Approach

Studies on N₂O emissions from California specialty crop systems were identified through an initial literature search in August 2017 and an update in September 2018 using the Web of Science and Google Scholar (keywords 'California', 'crop' and 'N₂O') and through personal communications with experts researching this topic. Only studies that provide direct N₂O emissions with a minimum flux sampling frequency of two times per month and the sampling period lasted at least two months or over the growing season are included to enable calculations of EFs. When experiments included more than one treatment, the results from individual treatments were entered into the database as separate observations. Data on direct N₂O emissions from specific practices are available in tomato, lettuce, wine grapes and almonds. Supplemental information from other regions is provided due to lack of information specifically from California specialty crops.

2.2. Brief Overview of Four Specialty Crops

Tomatoes: California produces 30% of the fresh tomatoes and 96% of the processed tomatoes in the U.S. [20]. Tomato is a warm-season crop that grows optimally with 23.9–35 °C day and 12.8–21.1 °C night temperatures. In the summer months, the Central Valley is the main production area, while in the spring and fall, Southern California supports significant production.

Lettuce: California produces around 68% of the lettuce in the U.S., and 43% of the nation's supply comes from the Central Coast region [48]. Lettuce is a cool-season crop that grows best with moderate

daytime temperatures (22.8 °C) and cool nights (7.2 °C) [49]. The state's major lettuce production areas are the Central Valley, Central Coast, the southern coast and the southern deserts.

Grapes: California produces over 90% of the wine grapes in the U.S., placing it among the top wine producers in the world [50]. Grapes grow in a wide range of temperatures (below freezing to over 37.8 °C) and are present in almost every county in the state [51].

Almonds: California currently produces 100% of the nation's commercial almonds [20]. Almonds require 200–400 annual chill hours (hours below 7.2 °C), respectively, to reach optimal yields. Almost all almonds are grown in the Central Valley (Sacramento and San Joaquin Valleys).

2.3. Estimating EF and State-Wide Emissions by Crop and Management Practice

Nitrous oxide emission factors (EFs) reported under each practice were either obtained from the literature directly or were calculated based on the field data reported in the literature. It was not possible to conduct a meta-analysis of available N_2O emissions from California specialty crops due to the limited number of studies, i.e., only 18 studies were identified in four specialty crop systems. Therefore, we reported N_2O EFs (both uncorrected and corrected for background flux; see calculations below) and estimated state level emissions for each specialty crop system under different management practices.

Here, the emission factor (EF) is defined as the percentage of input N emitted as N_2O . The calculation is as follows:

$$EF (percent, \%) = (N_2 O - N/input N) \times 100$$
(1)

If the N₂O background (no fertilizer input) emission was reported in the primary scientific literature, the EF calculation is adjusted as follows:

corrected EF (%) =
$$[(N_2O-N_{fertilizer treatment} - N_2O-N_{background})/input N] \times 100$$
 (2)

If a study did not investigate N_2O background emissions, N inputs from both unharvested crop residue (as recommended by IPCC guidelines) and fertilizer N are included in the EF calculation to correct the background of EFs as follows:

corrected EF (%) =
$$[N_2O-N_{fertilizer treatment}/(input fertilizer N + crop residue N)] \times 100$$
 (3)

The emission factors that are not corrected for the background flux are reported as "uncorrected EF". We also present the specific calculations for the determination of the EF associated with particular irrigation and cover crop practices in tomato systems. Assuming the difference in N₂O emissions between subsurface drip irrigation (SDI) and furrow, cover crop and no cover crop is constant across studies, the EF of N input under SDI or cover crop management can be calculated as follows:

$$EF_{SDI} = [EF_{furrow} \times (EF'_{SDI}/EF'_{furrow})]$$
(4)

Here, the emission factors EF'_{SDI} and EF'_{furrow} are acquired from Kallenbach et al. (2010), and EF_{furrow} is averaged from Kennedy et al. [40] and Burger and Horwath [39].

The EF of the cover crop for tomatoes was determined as follows:

$$EF_{cover \ crop} = [EF_{no \ cover \ crop} \times (EF'_{cover \ crop}/EF'_{no \ cover \ crop})]$$
(5)

Here, the emission factors $EF'_{cover crop}$ and $EF'_{no cover crop}$ are calculated based on the N₂O fluxes reported by Kallenbach et al. [41]. The value of $EF_{no cover crop}$ is averaged from Kennedy et al. [40] and Burger and Horwath [39] for furrow irrigation or calculated from Equation (1) for SDI.

The N₂O emissions baseline for each agricultural production system is defined as the N₂O emissions under standard practices, i.e., furrow irrigation, conventional tillage, no cover crop and

recommended N rate. The EFs used to calculate the statewide emissions are averaged from the EFs under the same practices (regardless of fertilizer rate) that are reported in the peer-reviewed scientific literature (Tables 1–4). If studies investigated more than one fertilizer N rate (excluding zero fertilizer rate) or fertilizer type, the EF is calculated for each treatment and the mean of the EFs is averaged across these treatments. If different combinations of irrigation, tillage and cover crop were investigated in different studies, specific calculations (see Equations (4) and (5)) are used to determine EFs for particular practices such as SDI and cover crop in tomatoes. If a study only reported seasonal emissions, a scaling factor (annual/seasonal) generated from other studies investigating the same practices was adopted to calculate the annual emissions. Only annual emissions and annual EFs were reported and discussed in this review. State-wide emissions are calculated by applying the same EF across all the planted area determined by CDFA Agricultural Statistics Review [52] regardless of soil types and microclimates. In this calculation, we assume the specialty crop systems are well-managed and growers use the N application rates recommended by USDA-NASS (https://quickstats.nass.usda.gov/).

3. Effects of Soil Management Practices on N_2O Emissions in Tomatoes, Lettuce, Grapes and Almonds

This section summarizes the current state of science on specific soil management practices in California's specialty crop systems and their effects on N₂O emissions. Supplemental information from other regions is provided to support the review when information specific to California is not available. We then focus on the soil management practices that are commonly adopted in four specialty crops—tomatoes, lettuce, grapes and almonds. These management practices are fertilization, irrigation, tillage and cover crops. When a management practice is missing for a given crop, there are no data available. We compare the N₂O EFs from the Intergovernmental Panel on Climate Change (IPCC) identified with published studies and then assess the N₂O inventory of these four crops (Tables 1–5). When possible, the relative impact of an alternative practice will be compared to the standard practice for each crop.

3.1. Fertilization

Synthetic and organic N fertilizers are an essential input to maintain high crop yields and quality. They are also the main source of N_2O emissions from the agricultural sector [4,12]. Fertilizers drive N_2O emissions from soil through their contribution to the availability of N substrates for soil microorganisms (e.g., nitrifiers and denitrifiers) and abiotic reactions, and through their influence on soil pH and oxygen availability during nitrification [53–55]. The influence of fertilizers on N_2O emissions is also soil- and climate-specific since variations in temperature and soil water content under different climates can significantly affect N_2O production through their influence on microbial activity and substrate availability [56,57]. The subsections on fertilizer will cover the effects of rate, type, placement, application timing and efficiency enhancers on N_2O emissions from specialty crop systems.

Location (Lat.; Long.)	Soil Texture	Irrigation Type	Tillage	Cover Crop	N Source	N Input (kg N ha ⁻¹)	Crop Residual N (kg N ha ⁻¹)	N ₂ O Emissions			Emission Factors (% of Applied N Emitted as N ₂ O, Uncorrected for Background Flux)		Emission F Applied N N ₂ O, Cor Backgrou	Emission Factors (% of Applied N Emitted as N ₂ O, Corrected for Background Flux) *		References	
								Growing Season (kg N ha ⁻¹)	Annual (kg N ha ⁻¹ yr ⁻¹)	Scaling Factor (Annual/Season)	Seasonal	Annual	Seasonal	Annual			
38°34′N; 121°56′W	Clay loam	Furrow	Standard	Ν	8-24-6; 28-0-5; CAN-17	402 ^a	73	2.01 ± 0.19	3.06 ± 0.19	1.52	0.85 ± 0.08	0.76 ± 0.05	$0.65{\pm}~0.06$	0.64 ± 0.04	Field	Kennedy et al., 2013	
		SDI	Reduced	Ν	8-24-6; UAN-32	205	111	0.58 ± 0.06	0.95 ± 0.05	1.64	0.28 ± 0.03	0.46 ± 0.02	0.28 ± 0.03	0.31 ± 0.02	Field	Kennedy et al., 2013	
38°32′30″N; 121°52′30″W	Yolo silt loam: 22% sand, 47% silt 31% clay				15-15-15;	0			$1.00\pm0.16^{\rm \ b}$		na	na	na	na	Field	Burger and Horwath, 2012	
		Furrow	v Standard	Standard	Standard	Standard	1 N	Ammonium sulfate;	75		na	$1.23\pm0.01~^{b}$		na	1.63 ± 0.01	na	0.31 ± 0.01
	Sitt, 51 /6 ciay				UAN-32	162		na	$1.81\pm0.18^{\text{ b}}$		na	1.11 ± 0.11	na	0.50 ± 0.07	Field	Burger and Horwath, 2012	
						225		na	$4.06\pm0.49~^{b}$		na	1.80 ± 0.22	na	1.36 ± 0.20	Field	Burger and Horwath, 2012	
						300		na	$4.34\pm0.87~^{b}$		na	1.45 ± 0.29	na	1.12 ± 0.24	Field	Burger and Horwath, 2012	
22021	D://1 1	Furrow	Standard	Ν	Ammonium nitrate	120	74	na	4.04 ^d		na	3.37 ^d	na	2.08 ^d	Field	Kallenbach et al., 2010	
32°N; 121°50′W	Yolo silt loam	Furrow	Standard	Y	Ammonium nitrate	227 ^c	74	na	7.99 ^d		na	3.52 ^d	na	2.65 ^d	Field	Kallenbach et al., 2010	
		SDI	Standard	Ν	Ammonium nitrate	120	74	na	2.09 ^d		na	1.74 ^d	na	1.07 ^d	Field	Kallenbach et al., 2010	
		SDI	Standard	Y	Ammonium nitrate	227 ^c	74	na	5.68 ^d		na	2.50 ^d	na	1.89 ^d	Field	Kallenbach et al., 2010	

Table 1. Nitrous Oxide Emission Studies in Tomatoes.

* Emission factors were corrected based on considering either crop residue N input or N₂O emissions from zero synthetic N input treatment. ^a 237 kg N ha⁻¹ was applied during tomato growing season and 165 kg N ha⁻¹ was applied during winter wheat growing season. ^b Tomato growing season. ^c 120 kg N ha⁻¹ synthetic N plus 107 kg N ha⁻¹ biomass N from cover crop residue. ^d Data based on only 13 hourly flux measurements. na: No data available; SDI: subsurface drip irrigation; N: no cover crop; Y: cover crop planted.

Location (Lat.; Long.)	Soil Texture	Irrigation Type	Tillage	Cover Crop	N Source	N Input (kg N ha ⁻¹)	Crop Residual N (kg N ha ⁻¹)	N ₂ O Emissions			Emission Factors (% of Applied N Emitted as N ₂ O, Uncorrected for Background Flux)		Femission Factors of Applied N s F Corrected for Background Flu		of as cor cor cor cor cor cor cor cor cor cor		Study Scale	References
								Growing Season (kg N ha ⁻¹)	Annual (kg N ha ⁻¹ yr ⁻¹)	Scaling Factor (Annual/Season)	Seasonal	Annual	Seasonal	Annual				
	Yolo silt loam: 46% sand, 32 silt, 22% clay	SDI ^a	Standard ^a	N	Commer-cial organic fertilizer	190	0.02	0.55 ± 0.09	0.92 ^c	1.67 ^b	0.30 ± 0.05	0.48	0.30 ± 0.05	0.48	Greenhouse	Pereira, 2014		
	Yolo silt clay loam: 19% sand; 48% silt; 34% clay	SDI ^a SDI ^a SDI ^a SDI ^a	Standard ^a Standard ^a Standard ^a Standard ^a	N	Commer-cial organic fertilizer	0 56 112 168 225		$\begin{array}{c} 0.16 \pm 0.12 \\ 0.35 \pm 0.05 \\ 0.79 \pm 0.06 \\ 1.00 \pm 0.21 \\ 1.15 \pm 0.13 \end{array}$	0.27 ° 0.58 ° 1.32 ° 1.67 ° 1.92 °	1.67 1.67 1.67 1.67 1.67	$\begin{array}{c} na \\ 0.63 \pm 0.08 \\ 0.71 \pm 0.05 \\ 0.60 \pm 0.13 \\ 0.51 \pm 0.06 \end{array}$	na 1.04 1.18 0.99 0.85	$na \\ 0.34 \pm 0.12 \\ 0.56 \pm 0.07 \\ 0.50 \pm 0.15 \\ 0.44 \pm 0.08$	na 0.55 0.94 0.83 0.73	Greenhouse Greenhouse Greenhouse Greenhouse	Pereira, 2014 Pereira, 2014 Pereira, 2014 Pereira, 2014 Pereira, 2014		
38.55N; 121.74W	Silt loam: 49% sand, 29 silt, 22% clay	SDI	Standard	Y	organic fish pellet fertilizer	260	na		1.09			0.42		0.32 ^d	Field	Suddick and Six, 2013		
36°40′14.4′N'; 121°36′22.5″W	Loam: 54% sand; 29% silt; 17% clay	SDI	Standard	N	UAN-32	84 168	15 19.5	0.34 ± 0.02 0.50 ± 0.04	0.64 ± 0.05 0.91 ± 0.14	1.89 1.82	0.4 0.3	0.76 ± 0.06 0.54 ± 0.08	0.34 0.27	0.65 ± 0.03 0.49 ± 0.04	Field Field	Burger and Horwath, 2012 Burger and Horwath, 2012		
						252 336	21.5 21.5	0.74 ± 0.04 1.00 ± 0.08	1.12 ± 0.11 1.47 ± 0.25	1.52 1.47	0.29 0.3	0.44 ± 0.04 0.44 ± 0.07	0.27 0.28	0.41 ± 0.04 0.41 ± 0.06	Field Field	Burger and Horwath, 2012 Burger and Horwath, 2012		

Table 2. Nitrous Oxide Emission Studies in Lettuce.

^a Simulated practice. ^b Value averaged from the scaling factors obtained from Burger and Horwath 2012. ^c Calculated based on scaling factor. ^d Background corrected using N₂O emission background reported in Pereira, 2014.

3.1.1. Fertilizer Rate

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The application rate of N fertilizer strongly influences N_2O emissions [39,55]. Generally, the relationship between N rate and N_2O emissions has been assumed to be linear and a default emission factor (EF) of 1% was adopted for use by the IPCC [58]. This N_2O EF approach has been used to construct most national GHG inventories [59]. However, field studies on multiple N fertilizer rates indicate that N_2O emissions often respond nonlinearly to increasing N rates across a range of climate, soil textures and fertilizer types [60,61]. Shcherbak et al. [62] demonstrated this nonlinear response of soil N_2O emissions to fertilizer N rates by conducting a meta-analysis on emissions data from 78 published studies with 233 site-years and at least three N input levels. These studies indicate that the Tier 1 N_2O accounting method adopted by IPCC, whereby N_2O emissions are assumed to be a simple fraction of N inputs, has the potential to underestimate or overestimate fertilizer derived N_2O emissions under certain circumstances. For example, in a California wheat system, only 0.1% of the applied N fertilizer was emitted as N_2O when N fertilizer was applied at a rate of 254 kg ha⁻¹. However, a much higher corrected EF (1.35%) was reported when the same rate of N fertilizer was applied in a California tomato system. This discrepancy indicates that crop characteristics, soil conditions, management practices and climate variations together control the contribution of N fertilizer to N_2O emissions.

In California specialty crop systems, N fertilizer application rates vary from crop to crop and location to location (https://quickstats.nass.usda.gov/). Nevertheless, the rate of N fertilizer application can only be refined to reduce N₂O emissions from these systems when it does not lead to undesired declines in crop yields [39,43]. In a model simulation study in California, De Gryze et al. [46] assessed that a 25% reduction in N fertilizer input would reduce N₂O emissions by -1.38 to -1.71 kg N ha⁻¹ yr⁻¹ but would also decrease tomato yields by -4 to -5.2%. Therefore, reduced N fertilizer input is the mitigation practice that may have the least likelihood to be adopted by farmers if it leads to reduced yields. Emissions from fertilizer N are often expressed as yield-scaled emissions [61]. Such scaling balances the inherent tradeoff between crop productivity and N₂O emissions, providing a metric that reflects the efficiency of N fertilizer use in a given agricultural production system. In general, practices that increase crop N use efficiency (NUE) are expected to reduce N₂O emissions, as applied N taken up by crops would not be available to soil microorganisms that produce N₂O. However, many studies showed that certain practices, e.g., fertilizer types and placement, can result in different N₂O emissions irrespective of NUE effects [61,63,64].

3.1.2. Fertilizer Type, Placement and Application Timing

The effect of N fertilizer type on direct N_2O emissions from soils is influenced by the form of the available N substrates, i.e., NH_4^+ , NO_3^- or organic N and short- and long-term changes in soil pH after application. In California, commonly used synthetic N fertilizers include urea-ammonium-nitrate (UAN), calcium-ammonia-nitrate (CAN), anhydrous ammonia, ammonium sulfate and urea, with an annual average of 0.576, 0.258, 0.237, 0.177 and 0.150 megatonnes, respectively, sold between 2007 and 2012 [65,66]. These fertilizers are ammonia-based and their long-term application generates soil acidity through nitrification [53,67]. Acidifying fertilizers tend to promote higher N_2O emissions through denitrification under anoxic soil conditions, especially in soils that have a low initial pH. Nitrification rates are generally higher for alkaline-forming than for acidifying N fertilizers under oxic soil conditions [53].

Location (Lat.; Long.)	Soil Texture	Irrigation Type	Tillage	Cover Crop	N Source	N Input (kg N ha ⁻¹)	N ₂ O Emissions		N ₂ O Emissions Emission Factors (% of Applied N Emitted as N ₂ O)* Scale		Emission Factors (% of Applied N Emitted as N ₂ O)*		References
							Growing Season (kg N ha ⁻¹)	Annual (kg N ha ⁻¹ yr ⁻¹)	Scaling Factor (Annual/Season)	Seasonal	Annual		
39°3.13′N;	Loam: 48% sand, 33% silt,	Drip	No till	Y	UAN-32	52 ^a	0.20 ± 0.02 ^b	5.04 ^c	28	0.38 ± 0.04	9.69	Field	Garland et al., 2011
121 58.755 W	19% clay		Standard				$0.14\pm0.04~^{b}$	3.92 ^c	28	0.27 ± 0.08	7.54		
39°3.13′N; 121°58.753′W	Loam: 48% sand, 33% silt, 19% clay	Drip	Standard	Y N	UAN-32	52 ^a 5.4	0.14 0.3	3.92 0.56	28 1.87	0.27 5.56	7.54 10.4	Field	Garland et al., 2014
38°17′58.68″N; 121°28′46.69″W	Sandy clay loam: 50% sand, 27% silt, 23% clay	Drip	Standard	Y	UAN-32	129 ^d 275 ^e	0.76 0.37	2 1.6	2.63 4.32	0.59 0.13	1.55 0.58	Field	Verhoeven and Six, 2014
36°19′14.88″N; 121°14′37.7″W	Loam	Drip	Standard	N Y Y	na	na	na na na	0.47 0.57 0.69			na na na	Field	Steenwerth et al., 2008
38°25′55″N; 122°24′48″W	Loam: 33% sand, 42% silt, 25% clay	Drip	Reduced Standard Standard	Y Y N	Potassium nitrate	43.4 ^f 42 ^f 27.6 ^f	na na na	$\begin{array}{c} 0.14 \pm 0.03 \\ 0.17 \pm 0.01 \\ 0.13 \pm 0.03 \end{array}$			0.32 ± 0.07 0.40 ± 0.02 0.47 ± 0.11	Field	Wolff, 2015
38°25′55″N; 122°24′48″W	Loam: 33% sand, 42% silt, 25% clay	Drip	Reduced Standard Standard	Y Y N	Potassium nitrate	38.8 g 44 g 38.6 g	na na na	$\begin{array}{c} 0.15 \pm 0.04 \\ 0.20 \pm 0.04 \\ 0.19 \pm 0.04 \end{array}$			$\begin{array}{c} 0.39 \pm 0.10 \\ 0.45 \pm 0.09 \\ 0.49 \pm 0.10 \end{array}$	Field	Wolff, 2015
38°17′49.7″N; 122°17′7.91″W	unknown	Drip	Standard	unknown	unknown	0 6 45	na na na	0.03 h 0.05 h 0.09 h			na 0.96 0.2	Field	Smart et al., 2006

Table 3. Nitrous Oxide Emission Studies in Grapes[†].

⁺ We focus mainly on the management practices that are commonly adopted in California grape cropping systems, summarize the N₂O EFs of wine grapes under these practices based on published studies. *The EFs are reported as uncorrected EFs since no corrections can be made based on either crop residue N input or control (no N input) treatment. ^a 5 kg N ha⁻¹ synthetic N plus 47 kg N ha⁻¹ organic N from cover crop residue. ^b Value calculated from berm (contributes 26%) and row emissions (contributes 74%). ^c Value calculated based on scaling factor. ^d 9.6 kg N ha⁻¹ synthetic N plus 119.6 kg N ha⁻¹ organic N from cover crop residue. ^e 66.4 kg N ha⁻¹ synthetic N plus 208.8 kg N ha⁻¹ organic N from cover crop residue. ^f 8.4 kg N ha⁻¹ synthetic N plus organic N from alley crop residue. ^g 16.8 kg N ha⁻¹ synthetic N plus organic N from the fluxes reported in the literature and were not included in the statewide emission calculation.

In California specialty crop systems, the effects of N fertilizer type on N_2O emissions are varied. Higher N_2O emissions were observed when almond orchards received UAN compared to the orchards that received CAN application [33,36]. Anhydrous ammonia applied by knife injection increased N_2O emissions compared to broadcast ammonium sulfate in a side-by-side field trial in a California wheat crop [61]. Higher N_2O emissions from urea application than from ammonium sulfate, ammonium nitrate and calcium nitrate have also been found in field trials and laboratory soil incubations [15]. In some of these experiments, both fertilizer type and placement varied among treatments, prohibiting isolation of the effect of individual practices on N_2O emissions.

Crop yield and N_2O emissions can be significantly affected by fertilizer placement. Fertilizer can be applied by spraying, banding, subsurface banding, broadcasting and fertigation (i.e., delivered through knife injection, surface, subsurface drip irrigation or microsprinkler). The choice of delivery depends on the crop and fertilizer types. Improper placement of fertilizers can lead to N loss, causing environmental impacts, reduced yield potential and decreased NUE, ultimately resulting in economic losses by growers [68]. In California specialty crop systems, fertilizer placement often is independent of tillage but dependent on irrigation practices. For example, in tomatoes, grapes and almonds, fertilizers are delivered with water via drip irrigation (i.e., surface, SDI or microsprinkler). Therefore, it is difficult to ascertain the sole effect of fertilizer placement on N_2O emissions from these systems.

It is a major challenge to synchronize soil N availability with crop demand when managing N fertilizer for crop production, and there is only one study in California that examines the timing of N application with plant uptake to reduce N_2O emissions [69]. An active and well-developed root system can utilize the most fertilizer N if it is applied to meet crop requirements at the appropriate growth stage. By doing so, the potential for soil microbial and chemical processes to transform the applied N into N_2O and other mobile forms such as nitrate is reduced; this, in turn, may lead to less water pollution and indirect N_2O emissions. However, the application of this concept needs to be examined more closely among California's specialty crops.

3.1.3. Fertilizer Efficiency Enhancers

In recent decades, enhanced efficiency fertilizer products, i.e., controlled- or slow-released fertilizers and nitrification inhibitors, have been developed to achieve synchrony of soil N availability with crop requirement and to reduce N losses through nitrate leaching and N₂O emissions. These efficiency-enhancing products include fertilizers coated with polymers, sulfur or calcium magnesium phosphate acting as physical barriers to control the release of plant available N, as well as nitrification inhibitors and urease inhibitors. Nitrification inhibitors suppress nitrifier activity over a certain period of time and prevent the oxidation of NH_4^+ to NO_2^- and consequently to NO_3^- ; urease inhibitors diminish the rate of urea hydrolysis in the soil [70] to reduce the increase in NH₄⁺ concentration. In tomatoes, polymer-coated fertilizer tended to be more effective when background N_2O emissions were higher and less effective under lower background emission rates [39]. The application of nitrification inhibitors has had no impact on annual N₂O emissions (Burger et al., data not published) in California tomatoes, where SDI has been gradually adopted [71]. This is most likely because of low N_2O emissions from these systems under SDI, wherein the effect of the nitrification inhibitor on the N_2O emissions from the fertilizer application was not detected experimentally. To date, no field trials have been conducted to investigate the effect of urease inhibitors on N₂O emissions from California specialty crop systems. Due to the regional variation in performance of these inhibitors [72], more robust data across various soil types, regional climates and management practices unique to California specialty crops will strengthen general conclusions about the effectiveness of nitrification and urease inhibitors.

39°01'N; 122°03'W

39°12′51″N;

38°57.451'N;

122°00'33"W

				_													
Location (Lat.; Long.)	Soil Texture	Irrigation Type	Tillage	Cover Crop	N Source	N Input (kg N ha ⁻¹)	Returned N (kg N ha ⁻¹)*	N ₂ O Emissions		Emission Factors (% Emission Factors (% of Applied N of Applied N N ₂ O Emissions Emitted as N ₂ O, Emitted as N ₂ O, Uncorrected for Corrected for Background Flux) #		Emission Factors (of Applied N Emitted as N ₂ O, Uncorrected for Background Flux		 Emission Factors (% of Applied N Emitted as N₂O, Corrected for Background Flux) † 		Study Scale	References
								Growing Season (kg N ha ⁻¹)	Annual (kg N ha ⁻¹ yr ⁻¹)	Scaling Factor (Annual/Season)	Seasonal	Annual	Seasona	l Annual			
35°30′37″N;	Sandy loam: 64% sand, 17% silt,	Microspri-nkler	No till	N	UAN: 4 times application	224	105		0.80 ± 0.19			0.35 ± 0.08		0.24 ± 0.06	Field	Schellenberg	
119 40 5 W	1976 Clay	Microspri-nkler	No till		CAN: 4 times application	224	102		0.53 ± 0.11			0.23 ± 0.05		0.16 ± 0.03		et al., 2012	
35°30′37″N; 119°40′3″W	Sandy loam: 64% sand, 17% silt,	Drip	No till	N	UAN: 4 times application	336	105 ^a	0.781	1.17	1.5	0.23	0.35	0.18	0.27	Field	Wolff 2015	
	19% clay	Drip	No till	1	UAN: 8 times application	336	105 ^a	1.036	1.55	1.5	0.31	0.46	0.23	0.35	rieiu	vvoiii, 2015	
		Drip	No till		CAN: 8 times application	336	102 ^a	0.511	0.77	1.5	0.15	0.23	0.12	0.17			
39°01′N;	Sandy loam	Drip	No till	Ν	unknown	236	80 ^b		1.61 ± 0.68			0.68		0.47	Field	Alsina et al.,	

 0.6 ± 0.25

 1.3 ± 0.6

 0.70 ± 0.02

 0.65 ± 0.07

Table 4. Nitrous Oxide Emission Studies in Almonds.

280 0.19 ± 0.07 122°4.527'W 13% clay 82 0.53 ± 0.19 0.18 2017 * N returned in hull and shall. [†] Emission factors were corrected based on including crop residue N in N input. ^a Value was adopted from Schellenberg et al., 2012. ^b Value was adopted

80^b

80^b

80 ^b

78

236

225

252

258

unknown

UAN32

UAN32

Ν

Ν

No till

No till

No till

Microspri-nkler

Drip

Microspri-nkler

from Decock et al., 2017.

Sandy loam: 67% sand, 19% silt,

14% clay

Sandy loam: 60% sand, 27% silt,

Field

Field

0.18

0.43

0.21

0.19

0.25

0.58

0.3

 0.25 ± 0.03

2013

Calrecycle,

2015

Decock et al,

Soil Syst. 2019, 3, 76

						Uncorre	cted for Background	d flux	Corrected	d for Backgrour	nd flux		IPCC Tier 1 Method Derived Statewide N2O-N Emissions, Gg CO2eq
Crop	Planted Area (1000 ha)	N Input (kg N ha ⁻¹)	Irrigation Type	Tillage	Cover Crop	Annual Emission Factors (% of Applied N Emitted as N ₂ O-N)	Statewide Annual N2O-N Emissions, Mg	Statewide Annual N2O-N Emissions, Gg CO2eq	Annual Emission Factors (% of Applied N Emitted as N ₂ O-N)	Statewide Annual N ₂ O-N Emissions, Mg	Statewide Annual N2O-N Emissions, Gg CO2eq	Number of Observations	
Tomato	Fresh-market tomato: 12.14; Processing tomato: 121.4	Fresh-market tomato: 108; Processing tomato: 178	Furrow	Standard	N	1.35 ± 0.24 ^a	309 ± 55	149 ± 25.8	0.79 ± 0.11	181 ± 25.2	84.8 ± 11.8	5	107
Tomato	Fresh-market tomato: 12.14; Processing tomato: 121.4	Fresh-market tomato: 108; Processing tomato: 178	SDI	Reduced	Ν	0.46 ± 0.02	105 ± 4.34	49 ± 2.03	0.31 ± 0.02	71.1 ± 4.58	33.3 ± 2.15	1	107
Tomato	Fresh-market tomato: 12.14; Processing tomato: 121.4	Fresh-market tomato: 108; Processing tomato: 178	SDI	Standard	Ν	0.70 ^b	160	75.1	0.41b	94	44	1	107
Tomato	Fresh-market tomato: 12.14; Processing tomato: 121.4	Fresh-market tomato: 108; Processing tomato: 178	Furrow	Standard	Y	1.41 ^c	323	151	1.01c	231	108	1	107
Tomato	Fresh-market tomato: 12.14; Processing tomato: 121.4	Fresh-market tomato: 108; Processing tomato: 178	SDI	Standard	Y	1.01 ^c	231	108	0.72c	165	77.3	1	107
Lettuce	131	166	SDI	Standard	Ν	0.75 ± 0.27	163 ± 59	76.3 ± 27.5	0.61 ± 0.04	133 ± 8.70	62.1 ± 4.07	9	102
Lettuce	131	166	SDI	Standard	Y	0.42	91.3	42.8	0.32	69.6	32.6	1	102
Grape	Wine grapes: 249; raisin grapes: 77.7; table grapes: 49.3	Wine grapes: 25; raisin grapes: 47; table grapes: 42	Drip	Standard	Ν	3.79 ± 2.67	437 ± 308	205 ± 144	na	na	na	3	55.9
Grape	wine grapes: 249; raisin grapes: 77.7; table grapes: 49.3	vine grapes: 25; raisin grapes: 47; table grapes: 42	Drip	Standard	Y	3.01 ± 1.32	347 ± 152	162 ± 71.3	na	na	na	6	55.9
Grape	Wine grapes: 249; raisin grapes: 77.7; table grapes: 49.3	Wine grapes: 25; raisin grapes: 47; table grapes: 42	Drip	Reduced/No till	Y	3.47 ± 2.54	400 ± 293	187 ± 137	na	na	na	3	55.9
Almond	450	150	Drip	No till	Ν	0.43 ± 0.15	290 ± 22.8	136 ± 10.7	0.31 ± 0.04	209 ± 27.0	98.0 ± 12.6	6	316
Almond	450	150	Mircrosprin	nkleno till	N	0.25 ± 0.05	169 ± 33.8	79 ± 15.8	0.19 ± 0.01	128 ± 6.75	60.1 ± 3.16	5	316

Table 5. California Specialty Crops Planting Acreage, Management Practices, N₂O Emission Factors and Statewide N₂O emissions.

^a Value is averaged from Kennedy et al. [40] and Burger and Horwath [39]. ^b Value is calculated from Equation (4) in Materials and Methods. ^c Value is calculated from Equation (5) in Materials and Methods. Note: the EFs present in this table were calculated based on limited studies.

3.1.4. Tomatoes and Fertilization

Tomatoes have a high N requirement. For example, Hartz and Bottoms [73] reported a mean aboveground biomass N accumulation of 296 kg ha⁻¹ in processing tomato fields that were produced conventionally for high yields. Generally, a seasonal N application rate of 170 kg ha⁻¹, with the majority applied by early-season side dressing, is sufficient for optimum yield [74]. Krusekopf et al. [75] reported that a seasonal total of no more than 112 kg N ha⁻¹ fertilizer was required to maximize tomato fruit yield in fields with soil nitrate content higher than 16 mg kg⁻¹ prior to side dress application. However, such low seasonal N application rates would be insufficient to support high-yield production over long periods; this is because fruit removal at harvest results in a loss of 150 to 230 kg N ha⁻¹ from the field (Burger and Horwath, unpublished data). In California, the most commonly used fertilizers are UAN-32 (urea ammonium nitrate, 32% N) and CAN-17 (calcium ammonium nitrate, 17% N) in subsurface drip and furrow irrigation in tomatoes [76,77]. The N application rates recommended by the USDA National Agricultural Statistics Service are around 108 and 178 kg N ha⁻¹ yr⁻¹ in well-managed fresh-market tomatoes and processing tomatoes, respectively (https://quickstats.nass.usda.gov/), though the actual N application rate for these crops is likely 45 kg N ha⁻¹ higher than the recommended rates [78].

Burger and Horwath [39] measured annual N₂O emissions under different N application rates, which ranged from zero to above recommended application rates in tomato fields. Their corresponding uncorrected EFs ranged from 1.11 ± 0.11 to $1.80 \pm 0.22\%$ when N application rates ranged from 75 to 300 kg N ha⁻¹ (Table 1). Unexpectedly, applying N at a rate (75 kg N ha⁻¹) below that required (162 kg N ha⁻¹) for optimal crop growth led to increases in the uncorrected EF (1.63% vs. 1.11%). However, when the N₂O background flux was considered, the difference in EF between these two fertilizer application rates vanished. In a conventionally managed (standard tillage, furrow irrigation) tomato field, Kennedy et al. [40,79] reported that 0.76 \pm 0.05% (uncorrected) or 0.64 \pm 0.04% (corrected, Table 5) of the applied N was lost as N₂O when N was applied at a rate of 237 kg ha⁻¹.

In this review, the average corrected EF for California tomato crop systems is $0.79 \pm 0.11\%$ under standard practices (standard tillage, furrow irrigation and no cover crop) (Table 5). This EF is comparable to the average overall EF of 0.5% for Mediterranean agriculture reported by Cayuela et al. [80], in which the EF was calculated based on a meta-analysis and corrected for background flux. If all tomato crop systems were managed under standard practices, the state-wide N₂O emission baseline for the N fertilization in tomato crop systems would be 84.8 ± 11.8 Gg CO₂eq yr⁻¹, 21% lower than the emission calculated using IPCC default EF (107 Gg CO₂eq yr⁻¹, Table 5).

3.1.5. Lettuce and Fertilization

Based on a survey carried out in lettuce systems found in the coastal valleys of central California, Hartz et al. [81] reported that the average seasonal N fertilizer application rate was around 184 kg N ha⁻¹, ranging from 30 to 437 kg N ha⁻¹. Fall application of N fertilization is not recommended due to the risk of leaching by the winter rains. Generally, small quantities of N (about 22 kg N ha⁻¹) are applied before or at planting, and 56–90 kg ha⁻¹ of N is side-dressed onto the beds. One or more additional side-dressings are common, typically several weeks apart. Generally, 11 to 17 kg ha⁻¹ of N is applied seven to 10 days prior to harvest to ensure that the crop color and growth rate are acceptable. The fertilization practices usually vary among growers and locations. The N application rate recommended for lettuce by the USDA National Agricultural Statistics Service is about 166 kg N ha⁻¹ (https://quickstats.nass.usda.gov/). Liquid fertilizers such as UAN-32 are most commonly used in drip irrigation. Composted manures and yard wastes are used to maintain soil structure in lettuce by some growers. Application rates are typically around 9 tons ha⁻¹.

Under greenhouse conditions, N_2O emissions ranged from 0.16 to 1.15 kg N ha⁻¹ when N fertilizers were applied between 0 to 225 kg N ha⁻¹ during the growing season [43]. The scaled annual N_2O emissions ranged from 0.27 to 1.92 kg N ha⁻¹; therefore, the annual EFs (corrected) of N input calculated using their data range from 0.34 to 0.56% (Table 2). Burger and Horwath [39] measured annual N_2O emissions under different N application rates, which ranged from 84 to 336 kg N ha⁻¹

in lettuce fields. They reported annual N₂O emissions between 0.64 to 1.47 kg N ha⁻¹. Their annual uncorrected EFs of N inputs ranged from 0.44 to 0.76%, and the annual corrected EFs ranged from 0.41–0.65% (Table 2). In this review, the average uncorrected EF is $0.75 \pm 0.27\%$ and corrected EF is $0.61 \pm 0.04\%$ from N inputs in lettuce under no cover crops, standard tillage and SDI practices (Table 5). If all lettuce fields in California were managed under the practices of SDI, standard tillage and no cover crop, the state-wide N₂O emission from N input in lettuce systems would be 62.1 ± 4.07 Gg CO₂eq yr⁻¹, 39% lower than the emission calculated using IPCC default EF (102 Gg CO₂eq yr⁻¹, Table 5).

3.1.6. Wine Grapes and Fertilization

Unlike vegetable crops and other fruit crops, grapes do not require intensive N input [82]. For example, the N requirement for raisin grape production in the San Joaquin Valley was 84 kg ha⁻¹, with approximately 35 kg ha⁻¹ removed by the crop [83]. This suggests that the annual N demand is approximately 25 to 50 kg ha⁻¹ depending on crop size. Excess N supply for grapes can be detrimental to vine growth and flavor, especially wine grapes, and can increase the potential for NO₃⁻ pollution and N₂O emissions. In California wine grapes, the most commonly used fertilizer is UAN-32 [84]. The average application rate recommended by the USDA National Agricultural Statistics Service is around 33 kg N ha⁻¹ yr⁻¹ in all types of grape, with 25 kg N ha⁻¹ yr⁻¹ in wine grapes (https://quickstats.nass.usda.gov/). In many wine grape regions, the target application is even lower, from 5 to 15 kg N ha⁻¹ yr⁻¹ ([85]).

The effects of fertilizer rate on N₂O emissions from wine grape vineyards have been examined in numerous studies. Drip irrigation and fertigation are the dominant irrigation and fertilizer practices in wine grape systems. Fertilizer N was delivered via the drip line exclusively in studies. In Napa County, Smart et al. [24] reported that N₂O emissions increased from 0.03 to 0.09 kg N₂O-N ha⁻¹ yr⁻¹ when N rates increased from 0 to 45 kg N ha⁻¹. Contrary to this trend, a higher uncorrected EF was found at the lower N rate. By using the flux reported in Smart et al. [24], the uncorrected EF was calculated as 0.96% when N applied at 6 kg N ha⁻¹, but 0.20% at 45 kg N ha⁻¹ (Table 3). In a two-year study, Wolff et al. [30,86] observed that annual N₂O emission rate was 0.13 kg N₂O-N ha⁻¹ yr^{-1} in the first year and 0.49 kg N₂O-N ha⁻¹ yr^{-1} in the second year in the grapes under standard tillage and without cover crop management; the uncorrected EFs we calculated from these different tillage practices treatments were 0.47% when vineyards received 8.4 kg N ha⁻¹ synthetic fertilizer plus organic N from alley crop residue in the first year and 0.49% when vineyards received 16.8 kg N ha⁻¹ synthetic fertilizer plus organic N from alley crop residue in the second year (Table 3). In Garland et al. [27], the calculated uncorrected EF was 10.4% when 5.4 kg N ha⁻¹ fertilizer was applied. In this review, the average uncorrected EF is 3.79% of N input in grapes under standard tillage, no cover crops and drip irrigation (Table 5). It was not feasible to calculate the corrected EFs due to a lack of data. If all grape systems were managed using these practices, the state-wide N₂O emissions from grapes would be 205 Gg CO₂eq yr⁻¹, 267% greater than the emission calculated using IPCC default EF (Table 5). This discrepancy may be due to the inability to calculate background-corrected N_2O emissions and the high variability of emissions among the studies (Table 3). In crop systems with low N inputs such as grape vineyards, any N₂O emissions from non-fertilizer sources (e.g., soil intrinsic N pool) could dramatically increase the uncorrected EF according to the EF calculation. The mitigation potential of alternative irrigation practices cannot be estimated because no field study has compared N₂O emissions from different irrigation practices in grapes. It is important for readers to understand that the large uncorrected EF does not indicate that N₂O emissions from grape systems are absurdly high—it simply indicates that it is difficult to separate emissions associated with N fertilizers from the background soil ecosystem emissions, since fertilizer application rates are relatively small in grape systems and are spread out over relatively long periods in the growing season.

3.1.7. Almonds and Fertilization

Compared to grapes, nut tree crops have higher nutrient requirements. Generally, mature almond trees use 80% of their total annual N requirement between March and mid-May-June to reach maximum yield. Applications of soluble N fertilizers are most commonly split throughout the annual production cycle. The types of N fertilizer used include urea, ammonium- and nitrate-based fertilizers. The N application rates recommended by the USDA National Agricultural Statistics Service are around 150 and 122 kg N ha⁻¹ for almonds and walnuts, respectively (https://quickstats.nass.usda.gov/). In a two-year almond orchard study, Schellenberg et al. [33] observed that when N fertilizers were applied at 224 kg N ha⁻¹, N₂O annual emissions from UAN tended to be higher than CAN though not significantly different. The uncorrected EFs were reported as 0.35% and 0.23% for UAN and CAN, respectively. Wolff et al. [86] reported that both the fertilization frequency and type significantly influenced N_2O emissions from an almond orchard, with higher N_2O emissions caused by a high frequency of fertilization (336 kg N ha⁻¹ split into 8 applications) compared to the standard application frequency (336 kg N ha⁻¹ split into 4 applications), and higher N₂O emissions from UAN than from KNO₃. In this review, a background uncorrected EF of 0.43% and a background corrected EF of 0.31% were calculated in California almonds under drip irrigation (Table 5). For comparison purposes, if the practices leading to this emission rate were used in all almond orchards in California (drip irrigation, no cover crops, no tillage), the state-wide N₂O emission from N input in these systems would be 98 \pm 12.6 Gg CO₂eq, 69.0% lower than the emission calculated using IPCC default EF (316 Gg CO₂eq yr⁻¹, Table 5).

3.2. Irrigation

Irrigation is an integral practice in specialty crop systems due to dry, warm summers found in Mediterranean climates. Innovative irrigation practices have emerged recently in response to California's Mediterranean climate and intense drought. Here, the role of irrigation in N₂O emissions is examined briefly. In this climate, most agricultural soils experience cycles of wetting and drying, which typically stimulate microbial activity and lead to large N₂O pulses through denitrification and ammonia oxidation [87,88]. Under flood irrigation, soils temporarily experience highly anoxic conditions, thus promoting denitrification. High denitrification rates do not necessarily indicate high N₂O emissions as extremely anoxic conditions can lead to complete denitrification [89]. During irrigation, soil moisture approaches saturation and oxygen diffusion is limited. This results in anoxic conditions that promote N₂O production [15], but once the soil is completely flooded only trace amounts of N₂O can be emitted to the atmosphere. At that point, the produced N₂O is trapped in the water and is further reduced to N₂ before diffusing to the atmosphere [90]. Optimal moisture conditions for N₂O production through denitrification and nitrification have been identified as 70–90% and <70% of water filled pore space, respectively [13]. A large amount of N₂O produced from ammonia oxidation pathways also has been observed under very low oxygen levels (i.e., 0.5% oxygen) in soil [15].

Comparing the relative effects of different irrigation practices, some have found that less N_2O is emitted from continuously flooded plots than from intermittently flooded plots in rice [91]. Under furrow irrigation, near-saturation conditions occur transiently for one or more days after irrigation. A large pulse of N_2O and CO_2 often occurs after the first irrigation event, with additional pulses after subsequent irrigation events dependent on substrate availability [88]. As another example, significantly higher N_2O emissions were observed from irrigation furrows (which are periodically flooded) compared with adjacent beds in tomatoes [39]. Spatial and temporal heterogeneity in environmental conditions, variation in frequency and volume of irrigation used, and resulting flux rates make it difficult to accurately and precisely quantify N_2O emissions from furrow irrigation.

Compared with flood and furrow irrigation, low-volume irrigation practices (i.e., surface, subsurface drip and microsprinkler techniques) usually have lower N_2O fluxes [41,92]. California specialty crop growers continue to adopt these irrigation practices due to their higher water use efficiency [71]. In almond orchards, N_2O emissions were lower during a fertigation event with a

microsprinkler system than those from a surface drip irrigation system [31,34]. In a meta-analysis of water management and fertilization in Mediterranean climates, Aguilera et al. [93] reported that cumulative N₂O emissions from drip irrigation practices were 2.0 kg N ha⁻¹ yr⁻¹, 5.8 kg N ha⁻¹ yr⁻¹ less than furrow irrigation. In subsurface drip irrigation, the soil surface is usually dry and soil moisture near the drip line is maintained between 20% and 30% water fill pore space between irrigation events. Evaporative losses are minimized, and the entire soil profile is rarely saturated [94,95]. Subsurface drip irrigation reduced N₂O by 1.95 kg N ha⁻¹yr⁻¹ compared to furrow irrigation in tomatoes [41] (Table 1). Studies with side-by-side experimental comparisons of subsurface drip irrigation, microsprinklers and/or surface drip irrigation are rare.

In sub-irrigation, evaporative losses are lower than they would be with surface irrigation since water is supplied directly to roots from below. However, N_2O emissions may increase under sub-irrigation due to the saturated soil profile promotes N_2O produced from denitrification and ammonia oxidation processes [15,96,97]. In California specialty crop systems, sub-irrigation is rarely used due to the low water tables, particularly in recent drought years [98,99].

In California, furrow irrigation has been commonly used for tomato production in the past. Currently, subsurface drip irrigation (SDI) is the primary irrigation method in the southern San Joaquin Valley (CA) and is increasing in other areas, but some tomato fields are still furrow irrigated in the northern San Joaquin Valley and in the Sacramento Valley [71]. The irrigation used in lettuce varies widely. In the inland deserts, furrow irrigation is commonly used [100], while on the Central Coast, growers mostly use sprinkler or drip irrigations. Since 2006, surface-placed drip irrigation has been increasing and now accounts for more than 30% of lettuce in the Salinas Valley. As grapes are not as sensitive as many crops to drought, growers aim for deficit irrigation. In wine grapes, as well as raisins and table grapes, drip irrigation is most common [101]. The use of micro-irrigation has been adopted by a majority of nut tree growers [102], while the use of flood irrigation has greatly declined as water availability for agriculture in California has become more restricted. The most common micro-irrigation practices for nut tree crops consist of aboveground drip (conventional drip) and stationary microjet sprinklers.

3.2.1. Tomatoes and Irrigation

Kennedy et al. [40] reported that the annual EF of N fertilization was lower in tomatoes under SDI combined with reduced tillage practices (uncorrected EF: 0.46%) than under furrow irrigation and standard tillage practices (uncorrected EF: 0.76%). However, it is difficult to ascertain the effect of SDI on the EF of N fertilization based on the study by Kennedy et al. [40] because no SDI treatment with standard tillage was applied. In a cover crop and irrigation study, Kallenbach et al. [41] compared the N₂O fluxes from tomato plots that received furrow irrigation and SDI. They observed that mean N₂O flux from the furrow irrigation treatment in rainy seasons tended to be higher than from SDI. When a cover crop was planted in winter, the mean N₂O flux from furrow irrigation was nearly 200% higher than from SDI, suggesting that SDI offers the potential to decrease N₂O emissions from tomatoes under cover crop management. Using the mean value of N_2O fluxes provided by Kallenbach et al. [41], we calculated the corrected EFs from furrow irrigation and SDI treatments (Table 1). The results show that the corrected EFs of N fertilization under furrow irrigation and SDI are 2.65% and 1.89% under cover crop management, and 2.08% and 1.07% under no cover crop management, respectively. However, these values have a high uncertainty because the frequency of gas sampling in Kallenbach et al. [41] was low, and no samples were collected between September and December. As a result, the mean N_2O fluxes, and therefore the EF, could be overestimated. Nevertheless, the comparison of EFs between furrow irrigation and SDI acquired from this study still can be used to estimate the EF under SDI and standard tillage management (see Equation (4) in Materials and Methods).

Here, the corrected EF of N fertilization under SDI and standard tillage practices is calculated as 0.41% (Table 5), comparable to the EF of 0.51% under drip irrigation derived from a meta-analysis of N₂O emissions from agricultural production systems in Mediterranean climates [80]. If all tomato

fields in California were managed under the practices of SDI, standard tillage and no cover crop, the state-wide N_2O emission from tomato systems would be 44 Gg CO_2 eq yr⁻¹, 48.1% lower than the same system under furrow irrigation. Adding the cover crop, total annual N_2O emissions would be 77.3 Gg CO_2 eq yr⁻¹, 28.4% less in the systems adopting SDI than furrow irrigation (Table 5). These results indicate that replacing furrow irrigation with SDI has the potential to mitigate GHG emissions from California tomato crop systems.

3.2.2. Almonds and Irrigation

The use of micro-irrigation systems has been adopted by a majority of California nut tree growers [102]. Schellenberg et al. [33] reported that in an almond system under microsprinkler irrigation, the annual N₂O emissions were 0.53 and 0.80 kg N ha⁻¹, corresponding to the reported EFs of 0.35% and 0.23% (background uncorrected) when UAN and CAN were applied through fertigation, respectively. Compared to microsprinkler irrigation, significantly higher N₂O emissions have been found in almonds under drip irrigation [34,35,86]. In this review, a background uncorrected EF of 0.25% and a background corrected EF of 0.19% were determined in California almonds under microsprinkler irrigation (Table 4). Based on these findings, if all almond orchards in California adopted the practice of microsprinkler irrigation, the state-wide N₂O emission from N input in these systems under no cover crop and no tillage would be reduced by 38.7% compared with the same systems under drip irrigation (Table 5).

3.3. Tillage

Tillage is a fundamental practice in agricultural management that changes soil chemical, physical and biological characteristics relevant to seedling germination and plant growth. The effects of tillage practices on soil N₂O emissions are due to changes in soil aeration status [103,104] and microbial activity [105,106]. The effect of conservation tillage and no-till relative to conventional tillage on soil N₂O emissions has received much attention. N₂O emissions vary widely in response to conservation tillage and no-till, ranging from increases, decreases and no change [107–109]. These contrary results have been attributed to differences in climate regime, N fertilizer placement, duration of tillage practice or a change from conventional to conservation or no-till practices, and soil texture [103,109–114]. No-till practices are considered integral to achieving California's air quality standards regulating airborne particulates smaller than 10 μ m. However, the long-term effect of no-till practices on GHG emissions in specialty crop systems remains an outstanding question.

Tomatoes are some of the most tillage-intensive annual crops in California, in part because such practices have provided historically reliable yields [115–118]. They rely heavily on tillage for bed preparation, weed control, pest and disease reduction on seedlings and postharvest residue incorporation [118]. Conservation tillage practices such as no-till and strip-till are usually defined as management practices that reduce tillage intensity and soil disturbance to maintain 30% or more of the soil covered by residues from previous crops after seeding [119,120]. A model simulation study projected that conservation tillage in California tomatoes has the potential to reduce N₂O emissions by -0.07 to -0.20 kg N ha⁻¹ yr⁻¹ [47]. Currently, less than 5% of tomato fields use conservation tillage practices in California (Mitchell and Horwath, personal communication). A "minimum-tillage" approach, which reduces the total number of tillage passes but not necessarily the overall disturbance of soil, is now being used with SDI to reduce weed densities [116,121]. Recent estimates from University of California Cooperative Extension suggest that this minimum tillage approach has been implemented in 90% of SDI tomato acres in the central San Joaquin Valley [122]. In lettuce, tillage mostly occurs during site preparation, and includes disking, subsoiling, chiseling, leveling land and preparing the seed beds [123]. Tillage is not used during the growing season.

In California grape vineyards, tillage practices include standard (complete) tillage and conservation tillage or no-till. Under standard tillage, the alleys are cultivated with standard disks and harrows, and this practice often is applied in alternating rows and years. A French plow or spring-hoe weeder

in late winter or early spring can be used to control weeds in the vine row instead of herbicide. No-till practices combined with cover crops recently have been promoted in vineyards, but potential drawbacks include impacts on residual-N in soil and vine balance [124]. Generally, tillage remains as minimum or no-till in almond orchards, except in orchards that receive flood irrigation.

Tomatoes and Tillage

Across conventional, low-input and organic tomatoes, Kong et al. [111] reported that reduced/minimum tillage (5 to 10 tractor passes) led to greater N₂O fluxes compared to standard tillage (12 to 15 tractor passes). However, robust annual N₂O emissions could not be calculated because measurements were only conducted monthly. Since reduced tillage is now being used widely with SDI, we calculated the total N_2O emissions from tomatoes under reduced tillage practices by adopting the corrected EF $(0.31 \pm 0.02\%)$ reported by Kennedy et al. [40] (Table 1). Therefore, if all tomatoes were managed with reduced tillage, SDI and no cover crops, the state-wide N₂O emission from N fertilization in tomato system would be 24.3% (or $-10.7 \text{ Gg CO}_2 \text{eq yr}^{-1}$) lower than the same system adopting standard tillage and 61% (or $-51.5 \text{ Gg CO}_2 \text{eq yr}^{-1}$) lower than the baseline of state-wide N₂O emissions (Table 5). These reductions are comparable to De Gryze et al. [46]'s simulation results, in which conservation tillage in California tomatoes was projected to reduce N_2O emissions by -4.4 to -46 CO_2 eq yr⁻¹ statewide compared with standard tillage. No study has been conducted yet to compare N₂O emissions from tomatoes under different tillage practices combined with furrow irrigation or cover crop. The other three crops did not have studies specifically comparing effects of different tillage practices and effects on N₂O or the effects of tillage on GHG emissions were conflated with other practices such as cover crops.

3.4. Cover Crops

Cover crops have been associated with increases in N₂O emissions from soils in Mediterranean climates [25,41,45,125]. In a meta-analysis of 26 published studies, including 106 observations of cover crop effects on N₂O emissions from the soil surface, over half of the studies observed higher N₂O emissions from soils under cover crops than without cover crops [126]. The incorporation of cover crops into the soil also promoted N₂O emissions in the short term (<4 weeks). This is because cover crops add a substantial amount of labile C and N to soil, thereby decreasing oxygen availability due to microbial respiration and increasing the microbial activity responsible for N₂O production [127–129]. Nevertheless, the temporal increases of N₂O emissions observed during cover crop decomposition were balanced by the periods when cover crops decreased emissions, underscoring the importance of long-term (i.e., entire year) monitoring to quantify the effect of cover crops on N₂O emissions [126]. In model simulation studies, De Gryze et al. [46,47] projected that cover crops (i.e., depositing organic C into soil) were considered, cover crop has potential to reduce GHG emissions by -1.07 to -2.50 Mg CO₂eq ha⁻¹ yr⁻¹ in four California crop systems [47].

Poor synchronization of mineralized N availability from cover crop decomposition and uptake by subsequent crops can lead to increases in soil N₂O production. Excess N, combined with available soil C, can increase N₂O derived from heterotrophic denitrification and ammonia oxidation pathways [56,130]. These effects vary with cover crop type. Leguminous residue may increase available soil N and subsequent N₂O emissions or, after harvest of the cash crop, non-leguminous species may rapidly take up surplus N in soil depending on their phenology and have a greater chance of reducing N₂O emissions [6,126]. Future studies focused on empirical data collection are needed to examine this hypothesis in California and elsewhere.

In California specialty crop systems, the benefits of adopting cover crops are gradually being recognized and the effects of cover crops on N_2O emissions have been examined in tomatoes and vineyards [25,27,41,86,131]. Wide adoption of cover crops still faces barriers due to the logistics and cost of operations and climate variation. Cover crops serve as green manures or are left as a surface

mulch after mowing or being burned down by herbicides [122]. Cover crop incorporation in annual production systems must occur at least four to six weeks before the agronomic crop to avoid problems with seed germination and seedling growth caused by immobilization of N or other nutrients (Horwath, personal communication). Cover crops are not widely used in tomatoes in California due to growers' concerns about lost opportunity costs involved in foregoing cash crop income and uncertainties about water use [117].

Cover crops are commonly grown under wine grapes but are found less commonly under table grapes and raisins due to limited winter precipitation in their growing regions. Growing cover crops in a vineyard can regulate vine growth by improving water penetration and soil fertility, and may also play a role in pest management [132,133]. Cover crops are not commonly grown in table grapes and raisins as they grow in regions with low winter rainfall. In tilled systems, cover crops are generally planted in the fall and mowed and tilled into the soil in the spring when the ground can be easily cultivated. In no-till systems, vineyards are seeded with species that will reseed themselves on an annual basis and replanted as needed with a no-till drill. Thereafter, the cover crops are mowed in spring and early summer, residues remain on the soil surface to decompose. The potential competition between cover crops and woody perennial crops for soil resources raises concerns in grapes and orchards [134], though recent work in irrigated wine grape vineyards suggests a decoupling of competition between grapevines and annual cover crops [124,133,135]. Cover crops in almond production are not widely used, and recent estimates by the California Almond Sustainability Program indicate that less than 5% of California almond orchards employ a cover crop.

3.4.1. Tomatoes and Cover crops

Kallenbach et al. [41] found significantly higher N₂O fluxes under cover crop practices than without cover crops. The EFs (background corrected) of N input that we calculated based on their study are 1.89% to 2.65% under cover crop management and 1.07% to 2.08% without cover crops (Table 1). The EF of N input and cover crops combined with SDI and standard tillage practices is calculated (see Equation (5) in Materials and Methods) as 1.01% (background uncorrected) and 0.72% (background corrected). The EF of N input and cover crops combined with furrow irrigation and standard tillage practices is 1.41% (background uncorrected) and 1.01% (background corrected) (Table 5). If all California tomatoes were managed with cover crops, SDI and standard tillage practices, the state-wide N_2O emission from N input in tomato systems would be 1.76 times greater than that from the same system without cover crops (Table 5). If all tomatoes were managed with cover crops, furrow irrigation and standard tillage, 127% more N2O would be emitted compared with the same systems with no cover crop (Table 5). That these results indicate that cover crop might not be an appropriate alternative practice to mitigate N₂O emissions from California tomato systems disregards the benefits from cover crops. They deposit organic C into soil, providing potential offsets for N_2O emissions. For example, after five years of cover crops in a tomato/cotton rotation, Veenstra et al. [136] reported that soil organic C (SOC) content increased in the top 30 cm soil by 4.0 to 4.9 Mg C ha⁻¹ compared to the absence of cover crops. Mitchell et al. [137] also observed that cover crops sequestered 0.46 to 0.63 Mg C ha⁻¹ yr⁻¹ more SOC than no cover crops. Using the soil C sequestration rate of 2.94 Mg CO_2 ha⁻¹ yr⁻¹ in tomatoes under cover crops [136], the global warming potential of adopting a cover crop practice is -285 Gg CO₂eq when SDI and standard tillage practices are adopted and -242 Gg CO₂eq when furrow irrigation and standard tillage practices are adopted. In other words, cover crops have the potential to decrease GHGs by -327 CO_2 eq yr⁻¹ to -370 CO_2 eq yr⁻¹ compare with standard practices. This reduction is higher than the mitigation potential of cover crops simulated by De Gryze et al. [46], in which only -164 CO_2 eq yr⁻¹ to -238 CO_2 eq yr⁻¹ GHGs emissions were projected to be reduced by cover crops. This discrepancy is likely partially due to the uncertainties of modeling simulation used by De Gryze et al. [46] and partially due to the limitations of the approach used in this review.

3.4.2. Lettuce and Cover crops

Unlike in tomatoes where the application of cover crops dramatically increases N_2O emissions and therefore EFs [41], Suddick and Six [42] reported an annual corrected EF of 0.32% for N inputs in the lettuce under cover crops (Table 2). This value is slightly lower than the annual corrected EF (0.41%) measured by Burger and Horwath [92] under a similar N application rate (260 vs. 252 kg N ha⁻¹) but without cover crops in a lettuce system. If all lettuce fields in California were managed with the practices of cover crop, standard tillage and SDI, the state-wide N₂O emission from lettuce systems would be 47.5% lower than the same system without cover crop (Table 5). However, side-by-side trials to compare N₂O emissions due to cover crops and in the absence of cover crops in lettuce systems are needed to address their influence on total annual GHG emissions.

3.4.3. Grapes and Cover Crops

Garland et al. [26] reported that when cover crops were present, N₂O emissions from vineyards under no-till practices were greater than the same system under standard tillage. The calculated annual EFs (uncorrected) of N input under these two combination practices were 9.69% and 7.54%, respectively (Table 3). However, Wolff et al. [30,86] observed that under cover crop practice in a wine grape vineyard, higher N₂O emissions were found from standard tillage than reduced tillage. In that case, 0.40–0.49% of the N input (uncorrected, calculated EF) was emitted as N₂O from the standard tillage system compared to 0.32–0.39% from the reduced tillage system. If all vineyards in California were managed with a cover crop, reduced tillage and drip irrigation, the state-wide N₂O emission from vineyard systems would be 187 CO₂eq yr⁻¹, 15.4% higher than the same system adopting standard tillage (Table 5).

In a wine grape vineyard, Garland et al. [27] observed that the annual N fixed by the leguminous cover crop under standard tillage led to N_2O emitted from soil at a rate of 3.92 kg N ha⁻¹yr⁻¹, resulting in a reported uncorrected EF as 7.54%. However, higher EF (uncorrected, 10.4%) was found in the treatments without cover crop than with cover crop. Steenwerth and Belina [25] and Wolff [86] also observed that higher N_2O EFs (uncorrected) in the no cover crop treatment than in the cover crop treatment in vineyards under standard tillage (Table 3). No study has compared the N₂O emissions from cover crop vs. no cover crop in reduced tillage vineyard system. If all vineyards in California adopt the practices of cover crop, standard tillage and drip irrigation, the state-wide N₂O emission from vineyard systems would be mitigated by 21% compared with the same systems that do not adopt cover crop (Table 5).

4. Limitations of the Approach and Gaps in Nitrous Oxide Emission Knowledge from California Specialty Crops

The approach we adopted to estimate the state-wide N_2O emissions for certain crops does not reveal broad understanding of how soil types and microclimates contribute to the total N_2O emissions because it is based on site-specific empirical studies. In California, 61% of crops receiving N fertilizer are in line with the recommended guidelines, but over 30% of crops (mainly vegetables and fruits) receiving N fertilizer exceed the maximum recommend amounts [78]. Thus, the state-wide N_2O emissions that were calculated by assuming all the crops receiving recommended N fertilizer rate in this review, could be underestimated. Better fertilizer usage reporting would be needed for each specialty crop to improve the accuracy of the state-wide GHG inventory.

Promising practices such as SDI, reduced tillage and no-till, and cover crops (Tables 1–5) merit further investigation of their potential to reduce N_2O emissions and their practical establishment in California agriculture. De Gryze et al. [46,47] simulated GHG emissions of California crop systems under conventional and conservation management practices using the DayCent model, and identified the mitigation potential of conservation tillage, cover crop and organic practices. Whereas these studies helped inform how shifts in soil management practices can reduce N_2O emissions, the DayCent model performance for N_2O simulation is limited by a lack of available empirical data from many California specialty crop systems to parameterize and calibrate the model. Currently about 87% of the cropland acreage in California can be modeled using DayCent (Easter, personal communication), with the remaining 13% reflecting the myriad specialty crops grown in the state.

More robust estimates of GHG emissions from California specialty crops still require additional research, particularly in side-by-side comparisons of annual N2O emissions across different crop species, soil types and practices. For example, Kallenbach et al. [41] compared the effect of irrigation type and cover crop on N_2O emissions in tomatoes. In that study, however, only hourly fluxes were reported, and 13 sample dates occurred over one year. Because of standard interpolation methods used for these data, annual N2O emissions and EFs calculated based on these hourly fluxes are much higher than in other studies (Table 1). High-frequency sampling over an entire growing season as well sampling across the entire year is needed to reduce the uncertainty of N₂O estimations. Other issues related to the estimation of N₂O emissions based on published studies include the over estimation of EFs under cover crop practices due to lack of information on the contribution of cover crop N to N_2O emissions, and the over estimation of EFs due to lack of information on the background (zero N) emissions and the resulted background-uncorrected EFs. For example, the uncorrected EFs for California almonds in Verhoeven et al. [23] ranged from 0.2–0.7%, while the corrected EFs for almond systems ranged from 0.18–0.47% in our review. Difficulties are also faced in estimating the N_2O mitigation potential for alternative practices, including SDI, conservation tillage, organic amendments like compost and manures and cover crops due to lack of research on these practices and their impacts on N₂O emissions across California agricultural landscapes. Limited geographic extent of these measurements also presents challenges to drawing reliable conclusions about the consistency of observed phenomena.

To estimate N_2O fluxes that reflect an integration of multiple management practices, research is also needed to improve empirical and processed-based model quantification of soil N2O emissions and therefore model development (i.e., DayCent). For example, more data are needed to better quantify: (1) soil N₂O production from different sources as affected by climate change, management practices, and soil biophysics; (2) mechanism behind soil N_2O emissions after SDI; (3) the interaction of fertilizer rate, type and delivery on N₂O emissions, especially for efficient irrigation methods like drip irrigation, microsprinklers and SDI; (4) the relative effects of crop-specific soil-plant interactions in the rhizosphere and how N_2O emissions may be different between different plant types; and (5) the effects on N_2O emissions cause by interactions between irrigation, fertilizer types and application methods, tillage, and climate. Development of a set of geographically stratified test sites at which factors known to affect N₂O emissions are varied to provide a robust empirical dataset for establishing Tier 2 and Tier 3 methods of IPCC (e.g., Long-Term Agricultural Research networks in USDA-ARS). The development and improvement of the DayCent model for California specialty crops also require information on how management practices influence nutrient cycling and water movement. For example, in woody perennials, better data on how floor management affects nutrient allocation is needed to more effectively model these crops. Other practices, such as plastic mulch used in strawberries, SDI in tomatoes and other crops, microsprinkler/drip irrigation in almond and grapes, and the application methods and placement of different synthetic fertilizers (i.e., alkaline-forming vs. acidifying N fertilizers) and organic amendments (i.e., fresh organics vs. compost), also warrant further characterization for use in the DayCent model.

Historic and emergent agricultural practices are being increasingly examined and employed for dual benefits for mitigation and adaptation to the changing climate. More studies are needed to provide robust data to estimate the benefits and tradeoffs associated with adoption of tillage regimes, compost and other organic amendments and cover crop management in these California specialty crops. For example, cover crops suppress weeds [138–140], and serve as 'intercrops' to fix N and build soil organic matter [41]. The mineralization and release of nutrients from cover crops and other organic amendments into plant available forms is generally slower compared to synthetic fertilizers, allowing

for immobilization by soil microorganisms, uptake by plants, increased soil organic matter, improved nutrient use efficiencies and reductions in leaching and nutrient loss [141–143].

Understanding how various practices reduce N₂O emissions from California specialty crops will continue to improve. For example, the CDFA Healthy Soils Initiative is supporting many studies on crop systems and practices that currently lack data (www.cdfa.ca.gov/healthysoils, accessed on 15 October 2018), but the key will be to continue these practices beyond the initial three years to achieve a semblance of equilibrium in improved soil conditions [103]. Nonetheless, these efforts will continue to illuminate the mechanistic understanding of soil N₂O production processes for the numerous specialty crops in California. A crucial need is the generation and curation of high-quality data from these specialty crop systems (e.g., USDA-ARS GRACEnet) that will be used to evaluate and refine predictive emissions models (e.g., DayCent). Other broader benefits derived from addressing this need include identification of practices that enable more efficient on-farm N fertilizer use, engagement of land users through education and outreach, and delivery of new data to inform policy makers' efforts to design farseeing strategies that meet both agricultural and environmental goals.

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