soil systems

Review

Irrigation and Greenhouse Gas Emissions: A Review of Field-Based Studies

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Abstract: Irrigation practices can greatly influence greenhouse gas (GHG) emissions because of their control on soil microbial activity and substrate supply. However, the effects of different irrigation management practices, such as flood irrigations versus reduced volume methods, including drip and sprinkler irrigation, on GHG emissions are still poorly understood. Therefore, this review was performed to investigate the effects of different irrigation management strategies on the emission of nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) by synthesizing existing research that either directly or indirectly examined the effects of at least two irrigation rates on GHG emissions within a single field-based study. Out of thirty-two articles selected for review, reduced irrigation was found to be effective in lowering the rate of CH_4 emissions, while flood irrigation had the highest CH_4 emission. The rate of CO_2 emission increased mostly under low irrigation, and the effect of irrigation strategies on N_2O emissions were inconsistent, though a majority of studies reported low N_2O emissions in continuously flooded field treatments. The global warming potential (GWP) demonstrated that reduced or water-saving irrigation strategies have the potential to decrease the effect of GHG emissions. In general, GWP was higher for the field that was continuously flooded. The major finding from this review is that optimizing irrigation may help to reduce CH_4 emissions and net GWP. However, more field research assessing the effect of varying rates of irrigation on the emission of GHGs from the agricultural field is warranted.

Keywords: GHG; nitrous oxide; methane; carbon dioxide; deficit irrigation; reduced irrigation; redox

1. Introduction

The global population is projected to rise to 9 billion by 2050 [1] and food production will have to double to meet food demands [2]. Intensification of agriculture, in particular through implementing various irrigation practices alongside improved high-yielding crops and application of fertilizers and pesticides, have already proven effective in increasing crop production through the green revolution [3]. However, intensified agriculture has also negatively impacted the environment through enhancing greenhouse gas (GHG) emissions—namely nitrous oxide (N_2O), carbon dioxide (CO_2), and methane (CH_4) [4] with agriculture now accounting for 10%–12% of total global anthropogenic GHG emissions [5]. Irrigation increases crop productivity, but its implementation often increases operational energy demand and potentially GHG emissions [5]. Furthermore, though irrigation has been a solution to boosting crop production, it can alter soil biogeochemical characteristics and soil structure, which may adversely impact soil carbon sequestration potential [6,7]. A better understanding of the link between various forms of irrigation and the subsequent impact on GHG emissions is needed; this effort is timely given that as of 2012, over 275 million hectares of agricultural fields are irrigated globally and this area is projected to increase [3].

Several biogeochemical processes control the rate of GHG emissions from soils, some of which are greatly impacted by soil moisture, including microbial respiration. Aerobic and anaerobic organic carbon respiration are significant contributing processes to CO_2 emission from soils [8], which are mostly driven by three biological processes, including microbial respiration, root respiration, and faunal respiration [9–11], all of which are greatly influenced by water availability within the crop root zone [12–17]. For decades, studies have shown that soil microbial production of CO_2 is related to water potential through a log-linear relationship when substrates and soil moisture are not limiting (e.g., [12,18]). Many studies have been dedicated toward elucidating the mechanisms responsible for the Birch effect, the phenomenon where a large pulse of CO_2 is released from soils upon re-wetting after a period of dry conditions [19]. Some of the mechanisms proposed include the sudden onset of microbially driven decomposition of microbial necromass accumulated during the dry period (e.g., [20]); lysis of live microbial cells [21]; the mineralization of intracellular compounds upon rewetting [22]; and enhanced substrate access by microbes as pore connectivity increases upon wetting [23]. Taken together, past studies show that the magnitude of the wetting pulse of CO_2 emission is influenced by the intensity and duration of the dry period and subsequent rewetting events, temperature, and substrate availability.

In general, wetting events have a greater impact on the carbon mineralization rate in arid climates than in humid climates [24]. In the context of agricultural soils, an irrigation event is more likely to lead to a greater increase in CO_2 pulse if the soil is less frequently irrigated or experiences fewer precipitation events. Similarly, N_2O can be produced in soils through biologically driven autotrophic nitrification and heterotrophic denitrification, which can be favorable under contrasting soil moisture conditions depending on soil texture and temperature [25–28]. Biological denitrification, the reduction of nitrate (NO_3^-) or nitrite (NO_2^-) for energy production, which mostly occurs in wet surface soils, is performed by phylogenetically diverse bacteria, a majority of which are heterotrophic linking NO_3^- or NO_2^- reduction to the oxidation of organic compounds. The last steps of dissimilatory nitrate reduction are catalyzed by nitrite and nitrous oxide reductases, which are encoded by *nir* and *nos* genes, respectively. Nitrous oxide reductases are responsible for reducing N_2O to N_2, which lowers GHG contribution from denitrification. After oxygen has been depleted within saturated zones, facultative anaerobes switch to respiring upon nitrate until oxygen is again available [29]. However, the production of N_2O by denitrification has been shown to be induced by the combined effect of higher oxygen content and moisture.

A number of denitrifying bacteria can also perform nitrification through reduced nitrogen compounds such as ammonia is oxidized to NO_2^- and NO_3^-, during which N_2O can be released in the presence of O_2. Nitrification is a two-step autotrophic oxidation of ammonium (NH_4^+) to NO_2^- by ammonium oxidizing bacteria or archaea (AOB and AOA, respectively) followed by oxidation of NO_2^- to NO_3^- by nitrite oxidizing bacteria (NOB). Culture-based studies have been used to unravel the mechanisms responsible for N_2O production identify the conditions that favor its production, which includes low dissolved oxygen concentrations, accumulation of nitrite, and dynamic conditions [30]. A dominant mechanism responsible for N_2O production under low oxygen conditions is nitrifier denitrification, which drives the reduction of NO_2^- by AOB using a variety of electron donors, including NH_4^+ [31]. A study led by Khalil et al. (2004) [32] demonstrated that nitrification rates decrease significantly as O_2 partial pressure is lowered within soil aggregates. However, the study's findings showed that although N_2O emissions were highest under anoxic conditions when denitrification dominated, N_2O emissions were primarily due to nitrification in the presence of O_2. In addition, secondary abiotic reactions including the reduction of nitrite by Fe^{2+} and Mn^{2+} also contribute to soil GHG emissions; the reactions producing these reduced redox active metals can also be dominated by anaerobic microbial respiration particularly in soils with high moisture content [33,34].

Unlike CO_2 and N_2O production, which can occur under both oxic and anoxic conditions, methanogenesis is a strictly anaerobic process that occurs during anoxic decomposition of organic matter [35]. Microbial methane production specifically is inhibited when redox potentials are greater than −200 mV [36]. However, recent reports have shown that methanogenesis can proceed within oxic soils due to the anaerobic interior of soil aggregates [37]. Methanogens are archaea that use a minimal number of substrates, including acetate, hydrogen, or methylated compounds, to produce methane. In the most methanogens, methyl coenzyme M reductase, the α subunit of which is encoded by the *mcrA* gene, catalyzes the last step of the reaction where oxygens in CO_2 are replaced by hydrogens to produce methane [38].

Soil moisture content, which is controlled by irrigation in most agricultural soils, plays an important role in modulating the release and consumption of GHGs [39,40]. Increased plant biomass and soil microbial activity as a result of higher volume or more frequent irrigation lead to increases in CO_2 and N_2O emissions compared to rainfed or non-irrigated soils [41]. This is because increased soil water content accelerates microbial respiration of soil organic matter, which enhances CO_2 flux [7]. Irrigation rate has also been shown to influence microbial metabolic processes, such as nitrification and denitrification responsible for the release of N_2O [42]. Bacterial activities under anaerobic conditions increased with irrigation, which resulted in elevated CH_4 emissions. Therefore, irrigation has a direct influence on GHG emissions.

Changes in soil moisture affects soil redox potential, which can significantly alter soil GHG emission rates [43,44]. The effects of soil redox on the emission of GHGs have been extensively studied in natural systems and under controlled environmental conditions [11,45–48]; however, soil redox potential was rarely documented during these studies [44]. Both soil redox potential and pH are important parameters that determine the thermodynamic favorability of biotic and abiotic reactions in soils; however, redox conditions are often overlooked particularly in agricultural studies, while soil pH tends to be emphasized and monitored in a majority of studies [49]. Changes in soil moisture greatly affect soil redox conditions, increase in soil moisture decreases soil redox potential, which in turn alters the likelihood and rate of GHGs emissions; some studies have shown that the change in redox potential is closely related to N_2O emission [44]. Studies have demonstrated that anoxic conditions will suppress CO_2 production due to a shift from aerobic to anaerobic microbial respiration, which occurs at a slower rate [50–52]. Effects of individual irrigation strategies on GHG emissions have been studied extensively; however, most studies compared a single irrigation treatment to the effects of dryland/rainfed (i.e., non-irrigated) treatment [53–55]. There are very few studies that have assessed the effect of varying rates of irrigation on GHG emissions [56,57] and, to our knowledge, a virtual absence of studies that incorporated mechanistic understanding the role of redox processes in GHG release in managed systems.

Severe droughts in many regions of the world has been attributed to climate change, which has led many farmers toward adopting deficit irrigation methods [58]. Reduced irrigation has the potential to decrease GHG emissions by optimizing the nitrogen and carbon turnover processes in soil [59]. An overall shift toward reduced irrigation strategies can decrease GHG emission from managed lands, particularly in arid systems, however, the mechanistic relationship between different rates of irrigation and GHG emissions are still not well understood. In this review, we present and discuss GHG flux observations from studies that compared at least two irrigation treatments in the same cropping systems with otherwise identical management practices. We then discuss the reported or likely mechanisms underlying the effects of reduced irrigation on GHG flux from managed lands, while also providing insights into the potential role of redox processes.

2. Materials and Methods

Peer-reviewed technical journal articles that examined the effect of deficit irrigation rates on GHG emissions were included in this review. References were extensively searched using the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines [60] in three most common databases—Web of Science, SCOPUS, and JSTOR. The literature search was conducted in February 2019 using five keywords in the following order: “irrigation”, “N_2O”, “agriculture”, “carbon”, and “methane.” The search was updated using the Web of Science database in November 2019 where only four keywords in the following order: “irrigation”, “N_2O”, “carbon”, and “methane” were used. All relevant articles fulfilling the following criteria were included in the study: (1) Studies should have at least two different irrigation treatments and (2) Studies had to report at least one of the following GHG emission-N_2O, CH_4, and CO_2 (only the studies that fulfill the first criterion was tested for this second criterion). Yield and other pertinent parameters were also recorded when available in the article. Experiments that were replicated, randomized, and were conducted in the field with well-described protocols were included in this study. Abstracts, book chapters, non-English articles, greenhouse experiments, non-research publications, and review papers were not included in the study.

GHG emissions and other relevant data were retrieved from tables and graphs presented in publications. For any multi-year studies, data presented were averaged, and only the mean values are presented and discussed. Values that were presented in plots were extracted using WebPlotDigitizer Version 4.1 [61]. Whenever feasible, data were rounded to the nearest whole number for all response parameters. However, since N_2O emissions were very small in many cases, their mean values were rounded mostly to one or two decimal places (sometimes up to three decimal places to show as least one significant figure). The same applies to the CH_4 emissions whenever they had low emissions (Table 1). Once all the papers to be included in the study were identified, effects of irrigation systems characteristics and management strategies on the emissions of GHG were studied and the results are presented with the aim of identifying current knowledge gaps on the net effects of irrigation on GHG emissions [7]. In this report, any water-saving strategies such as sprinkler irrigation, drip irrigation, optimized irrigation, alternate wetting and drying (AWD), or other low-volume irrigation practices are referred to as reduced irrigation unless otherwise mentioned.

Using the five keywords search terms (“irrigation”, “N_2O”, “agriculture”, “carbon”, and “methane”), a total of 207 papers were identified in the first phase for manuscripts that fulfilled the first criterion. Among the papers, Web of Science, SCOPUS, and JSTOR contributed 30, 55, and 122 articles, respectively. One paper from an outside source was later added. Therefore, there were 208 papers during the initial review. The number of articles decreased to 172 after removing duplicates (n = 14), and books and abstract (n = 22). Title and abstract screening was done and any paper that did not mention irrigation/water and one of GHG of our interest was excluded. This screening step removed 113 articles leaving 59 articles. All 59 studies were reviewed thoroughly and the number of articles further decreased to 17 after excluding review papers, non-English papers, greenhouse experiments, and studies without at least two irrigation treatments. The articles included in the review were then updated in November 2019 using the four-keyword search terms (“irrigation”, “N_2O”, “carbon”, and “methane”) in the Web of Science database. A total of 142 papers were identified in the initial search. After removing books, and abstracts, the number decreased to 138. Title screening to determine the suitability of paper eliminated 88 papers bringing down the total number of papers to 50. After assessing the full text, 25 papers were excluded because they were either reviews, greenhouse studies, or studies without multiple irrigation treatments. Only 25 papers were found to be eligible for this study. Out of which, 10 were duplicates of the first search. Therefore, only 15 papers were included from this updated search. Overall, following the PRISMA guideline [60], findings from the 32 selected studies were included for the review purpose.

The impact of different irrigation strategies on greenhouse gas emission was compared by calculating global warming potential (GWP). CH_4 and N_2O emissions were taken into consideration when calculating GWP. The GWP coefficient 298 and 34 for N_2O and CH_4, respectively, were used to convert N_2O and CH_4 to CO_2 equivalents. These coefficient values were retrieved from IPCC fifth assessment report [62]. We used an equation $GWP_{(N_2O + CH_4)} = (298^* N_2O \text{ kg ha}^{-1}) + (34^* CH_4 \text{ kg ha}^{-1})$ to calculate GWP on a 100-yr time horizon [63]. Whenever all three GHGs (N_2O, CO_2, and CH_4) are reported, $GWP_{(N_2O + CH_4 + CO_2)}$ was calculated using the equation $CO_2 + (298^* N_2O \text{ kg ha}^{-1}) + (34^* CH_4 \text{ kg ha}^{-1})$.

Table 1. Summary of the articles included in the review process. Following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines, a total of 32 articles were selected for this study. For any multi-year studies, data presented were averaged, and only the mean values are presented.

Article Number	References	Crop	Location	Irrigation Treatments*	Irrigation (mm)	N_2O (kg/ha) §	CH_4 (kg/ha) §	CO_2 (kg/ha) §	Yield (kg/ha)	GWP (N_2O + CH_4) (kg CO_2 e ha^{-1}) ^	GWP-All (kg CO_2 e ha^{-1}) ^
1	Ahn et al., 2014 [64]	Paddy	South Korea	Continuous Flooding	-	0.003	286	-	5289	9725	-
				Water Saving	-	0.02	62	-	5670	2114	-
2	Ali et al., 2013 [65]	Paddy	Bangladesh	Continuous irrigation	-	0.55	124	-	4290	4380	-
				Intermittent irrigation	-	0.98	90	-	4350	3352	-
3	Berger et al., 2013 [66]	Paddy	South Korea	Traditional irrigation	-	0.88	2328	-	4356	79,414	-
				Intermittent irrigation	-	−0.88	706	-	4638	23,742	-
				FDFM	-	0.02	1541	-	7118	52,400	-
4	Edwards et al., 2018 [67]	Tomatoes	Canada	Subsurface drip	-	4.2	-	2620	-	-	-
				Surface drip	-	3.89	-	2395	-	-	-
5a	Fangueiro et al., 2017 (No-tillage) [68]	Paddy	Spain	Flood	2300	14.24	125	5353	6100	8477	13,830
				Sprinkler	700	6.03	−0.38	5802	5197	1784	7586
5b	Fangueiro et al., 2017 (Tillage) [68]	Paddy	Spain	Flood	2300	10.6	353	6680	6677	15,161	21,841
				Sprinkler	700	7.95	3	10,222	3567	2455	12,677
6	Fentabil et al. 2016 [69]	Apple	Canada	High frequency irrigation	-	0.68	-	-	-	-	-
				Low frequency irrigation	-	0.49	-	-	-	-	-
7	Franco-Luesma et al., 2019 [70]	Maize	Spain	High frequency irrigation	608	1.41	−0.17	2090	14,840	414	2504
				Low frequency irrigation	608	1.36	−0.21	2050	15,030	398	2448
8	Gupta et al., 2016 [63]	Paddy	India	ZTW-TPR	-	0.6	39	-	5180	1513	-
				ZTW-IWD	-	0.77	27	-	4970	1139	-
9	Haque, kim et al., 2016 [71]	Paddy	South Korea	Continuous flooding	-	0.5	258	3354	6700	8904	12,258
				Mid-season drainage	-	0.62	133	4935	6600	4690	9625

Table 1. *Cont.*

Article Number	References	Crop	Location	Irrigation Treatments*	Irrigation (mm)	N_2O (kg/ha) §	CH_4 (kg/ha) §	CO_2 (kg/ha) §	Yield (kg/ha)	GWP (N_2O + CH_4) (kg CO_2 e ha^{-1}) ^	GWP-All (kg CO_2 e ha^{-1}) ^
10	Haque et al., 2016 [72]	Paddy	South Korea	Continuous flooding	-	0.52	240	3864	5500	8315	12,179
				Intermittent drainage	-	0.73	140	4606	5300	4978	9584
11a	Kallenbach et al., 2010 (WLLC) [73]	Tomato	USA	Furrow irrigation	886	0.02 kg/ha/d	-	85 kg/ha/d	79,000	-	-
				Surface drip irrigation	381	0.005 kg/ha/d	-	74 kg/ha/d	79,000	-	-
11b	Kallenbach et al., 2010 (NCC) [73]	Tomato	USA	Furrow irrigation	886	0.006 kg/ha/d	-	52 kg/ha/d	79,000	-	-
				Surface drip irrigation	381	0.005 kg/ha/d	-	62 kg/ha/d	79,000	-	-
12	Kumar et al., 2016 [74]	Paddy	India	Continuous flooding	1200	1.04	35	1135	4940	1488	2623
				−20 kPa	840	1.25	24	1298	4850	1194	2491
				−30 kPa	726	1.27	20	1416	4810	1043	2459
				−40 kPa	673	0.98	17	1118	3780	863	1980
				−50 kPa	643	0.89	15	1040	3220	777	1817
				−60 kPa	608	0.84	14	1017	2560	722	1739
13	Li et al., 2019 [75]	Wheat	China	High irrigation	630	0.97	−1.86	7020	6790	226	7246
				Low irrigation	420	0.86	−2.01	7350	7587	188	7538
14a	Liang et al., 2017 (Early rice) [76]	Paddy	China	Farmer's irrigation practice	137	1.52	165	-	7387	6053	-
				Optimize irrigation	15	1.65	131	-	7477	4946	-
14b	Liang et al., 2017 (Late rice) [76]	Paddy	China	Farmer's irrigation practice	283	2.64	209	-	8362	7900	-
				Optimize irrigation	196	2.97	121	-	8683	5013	-

Table 1. *Cont.*

Article Number	References	Crop	Location	Irrigation Treatments*	Irrigation (mm)	N_2O (kg/ha) §	CH_4 (kg/ha) §	CO_2 (kg/ha) §	Yield (kg/ha)	GWP (N_2O + CH_4) (kg CO_2 e ha^{-1}) ^	GWP-All (kg CO_2 e ha^{-1}) ^
15	Linquist et al., 2015 [57] ¶	Paddy-Soybean	USA	Continuous flooding	762	0.05	86	-	10,260	2922	-
				AWD/40 Flood	654	0.25	47	-	10,170	1671	-
				AWD/60	616	0.32	4	-	9730	246	-
				AWD/40	514	0.59	5	-	8970	337	-
16	Maris et al., 2016 [77]	Paddy	Spain	Continuous irrigation	-	−1.4	−87	6045	9572	−3378	2667
				Intermittent irrigation	-	0.73	−156	8416	6291	−5080	3336
17	Maris et al., 2015 [78]	Olive	Spain	Surface drip irrigation	449	0.07	−48	753	2144	−1593	−840
				Subsurface drip irrigation	242	0.02	−63	781	2198	−2135	−1354
18	Riya et al., 2014 [79]	Paddy	Japan	Continuous flooding	-	-	509	15,422	9707	-	-
				Intermittent flooding	-	-	306	9253	7167	-	-
19	Samoy-Pascual et al., 2019 [80]	Paddy	Philippines	Continuous flooding	1123	1.77	52	-	7190	2282	-
				AWD	584	3.39	42	-	7090	2431	-
20a	Scheer et al., 2008 [81]	Winter wheat	Uzbekistan	High irrigation intensity	900	0.9	below detection limit	-	-	-	-
				Low irrigation intensity	800	0.6	below detection limit	-	-	-	-
20b	Scheer et al., 2008 [81]	Cotton	Uzbekistan	High irrigation intensity	463	4.4	below detection limit	-	-	-	-
				Low irrigation intensity	373	2.4	below detection limit	-	-	-	-
21	Scheer et al., 2012 [56]	Wheat	Australia	High irrigation	244	0.75	-	-	3100	-	-
				Medium irrigation	161	0.43	-	-	1900	-	-
				Low irrigation	65	0.45	-	-	1600	-	-
22	Scheer et al., 2014 [82]	Cotton	Australia	High irrigation	734	0.82	-	-	1560	-	-
				Medium irrigation	633	1.07	-	-	1070	-	-
				Low irrigation	586	0.8	-	-	730	-	-

Table 1. *Cont.*

Article Number	References	Crop	Location	Irrigation Treatments*	Irrigation (mm)	N_2O (kg/ha) §	CH_4 (kg/ha) §	CO_2 (kg/ha) §	Yield (kg/ha)	GWP (N_2O + CH_4) (kg CO_2 e ha^{-1}) ^	GWP-All (kg CO_2 e ha^{-1}) ^
23a	Tang et al., 2018 (1-yr tillage) [83]	Paddy	China	Continuous flooding	-	2.3	35	17,468	-	1879	19,347
				Intermittent flooding	-	2.90	30	22,241	-	1888	24,129
23b	Tang et al., 2018 (57-yr tillage) [83]	Paddy	China	Continuous flooding	-	2	323	21,202	-	11,592	32,793
				Intermittent flooding	-	2.4	252	26,496	-	9276	35,772
24	Wang et al., 2016 [84]	Wheat	China	Flood irrigation	240	0.012 kg/ha/d	−0.01 kg/ha/d	158 kg/ha/d	7651	-	-
				Surface drip irrigation	160	0.01 kg/ha/d	−0.01 kg/ha/d	155 kg/ha/d	7355	-	-
				Sprinkler irrigation	203	0.012 kg/ha/d	−0.01 kg/ha/d	160 kg/ha/d	8304	-	-
25	Win et al., 2013 [85]	Paddy	Japan	Continuous Flooding	1952	1.2	238	-	19,080	8450	-
				Water Saving	248	1.4	84	-	19,600	3273	-
26a	Wu et al., 2018 (Early season) [86]	Paddy	China	CF ¥	-	0.00	249	-	4636	8476	-
				F-D-F	-	0.07	131	-	3964	4488	-
				F-RF	-	0.12	55	-	3850	1913	-
26b	Wu et al., 2018 (Late season) [86]	Paddy	China	CF ¥	-	−0.01	505	-	6250	17,177	-
				F-D-F	-	0.04	242	-	6280	8243	-
				F-RF	-	0.2	57	-	5101	1981	-
27	Wu et al., 2014 [59]	Cotton	China	Furrow irrigation (mulch-free)	-	1.71	−3	-	1760	410	-
				Drip irrigation (plastic film mulching)	-	1.09	−9	-	2020	23	-
28	Xu et al., 2015 [87]	Paddy	China	Continuous flooding	1074	8.2	955	9249	6695	34,914	44,163
				Flooded and wet intermittent	671	9.2	365	12,137	6632	15,152	27,289
				Flooded and dry intermittent	633	10.3	176	18,046	6006	9053	27,099

Table 1. *Cont.*

Article Number	References	Crop	Location	Irrigation Treatments*	Irrigation (mm)	N_2O (kg/ha) §	CH_4 (kg/ha) §	CO_2 (kg/ha) §	Yield (kg/ha)	GWP (N_2O + CH_4) (kg CO_2 e ha^{-1}) ^	GWP-All (kg CO_2 e ha^{-1}) ^
29a	Xu et al., 2016 (Paddy) [88]	Paddy	China	Continuous flooding	1022	6.76	769	10,858	8110	28,176	39,034
				Flooded and wet intermittent	440	8.44	280	13,367	7830	12,029	25,396
				Rain-fed with limited irrigation	195	11.28	70	17,958	7080	5752	23,709
29b	Xu et al., 2016 (Rapeseed) [88]	Rapeseed	China	Continuous flooding	1022	12.05	24	11,139	1630	4415	15,554
				Flooded and wet intermittent	440	10.49	18	10,986	1710	3724	14,710
				Rain-fed with limited irrigation	195	8.31	8	10,187	2150	2751	12,938
30	Yang et al., 2012 [89]	Paddy	China	Flood irrigation	1135	0.96	117	-	8435	4267	-
				Controlled irrigation	324	1.07	22	-	8460	1058	-
31	Yang et al., 2019 (with biochar) [90]	Paddy	China	Flood irrigation	1038	1.99	426	-	8170	15,060	-
				Controlled irrigation	539	3.58	100	-	7940	4479	-
32	Zschornack et al., 2016 (growing season 2) [91]	Paddy	Brazil	Continuous Flooding	-	0.09	303	-	10,666	10,328	-
				Sparse intermittent irrigation	-	2.8	46	-	10,396	2398	-
				Frequent intermittent irrigation	-	1.05	89	-	10,853	3339	-

Mean values were mostly rounded to the nearest whole number; exception was N_2O and some of CH_4 emissions (up to three decimal places). FDFM-Flooding-midseason drainage-reflooding-moist intermittent irrigation without water logging; WLLC-winter legume cover cropping; NCC-no cover cropping. * Irrigation treatments mentioned in the table reflect what it was called in the article. Same irrigation treatment names are independent from one study to another. §-same units across the column unless otherwise mentioned. ¶ AWD implies alternate wetting and drying. The numeric number followed by AWD represents percent of saturated volumetric water when fields were re-flooded. ¥ CF = continuous year-round flooding with a 2–10 cm water layer; F-D-F = flooding during the rice season except for drainage at midseason and harvest time; F-RF = flooding for transplanting and tillering with no further irrigation. ^ GWP is summed over a growing season; all crops considered are annual crops. GWP-All is the net global warming potential calculated using all three greenhouse gases (GHGs) (N_2O, CO_2, and CH_4).

3. Results

3.1. Effects of Irrigation on N_2O Emissions

The impact of reduced irrigation on N_2O emissions has been examined in many cropping systems globally, and though there are clear interactions between reduced or deficit irrigation on other management practices including fertilization and tillage, findings appear to be inconsistent. Some studies show that reduced irrigation generally leads to a decrease in N_2O emissions, while others showed contrasting findings. For example, a study performed by Fangueiro et al. [68] in a loam soil in Spain examined the interaction of tillage and reduced irrigation on N_2O emissions from rice fields. Under no-till management, they showed that the average N_2O emissions from a sprinkler-irrigated paddy field were 6.03 kg N_2O ha^{-1}, 57% less than fields that were under continuous flood irrigation (14.24 kg N_2O ha^{-1}). Even when conventional tillage was practiced, N_2O emission remained lower under sprinkler irrigation (7.95 kg N_2O ha^{-1}) with a 25% lower total N_2O emission compared to flood-irrigated fields (10.6 kg N_2O ha^{-1}). The average total volume of water used in the sprinkler-irrigated treatments (700 mm) was 1600 mm less than in the flooded systems (2300 mm). Similarly, reduced irrigation leads to a decrease in N_2O emissions during the production of other crops. Li et al. [75] found that N_2O emissions decreased 12% (by 0.11 kg N_2O ha^{-1}) in low irrigation treatment fields as compared to emissions from high volume irrigation treatments (0.97 kg N_2O ha^{-1}) in a wheat experiment performed in a sandy loam soil in China. Similarly, reduced N_2O emissions were also observed in winter wheat and cotton fields in Uzbekistan, with low irrigation intensity, where emission was 33% (0.3 kg N_2O ha^{-1}) and 45% (2 kg N_2O ha^{-1}) lower compared to high irrigation intensity, respectively [81]. Berger et al. [66] observed a decrease in N_2O emission from rice paddies in a study based in Korea when fields were intermittently irrigated as compared to traditionally irrigated (i.e., continuously flooded). Results were consistent even with finer textured soils where Scheer et al. [56] found from a wheat study performed in clay soil in Queensland, Australia, that N_2O emissions were reduced by 40% from 0.75 kg ha^{-1} under high irrigation treatment to 0.45 kg ha^{-1} under low irrigation treatment.

A 2-yr study done by Kumar et al. [74] in eastern India found a significant decrease in N_2O emissions with an application of a reduced amount of irrigation water. In the study, the effect of continuous flooding and five different irrigations applied based on soil water potential (−20 kPa, −30 kPa, −40 kPa, −50 kPa, and −60 kPa) were assessed. Irrigation treatments that had soil water potential between −40 to −60 kPa, as compared to treatments where more amounts of irrigation water were applied (continuous flooding, −20 kPa, and −30 kPa), yielded significantly lower N_2O compared to continuous flooding; water usage in −60 kPa was up to 49% less than the continuous flooding. Reduction in N_2O emissions of up to 68% was reported by Maris et al. [78] when two water-saving irrigation strategies including drip irrigation (average irrigation water applied 449 mm) and subsurface drip irrigation (average irrigation water applied 241.50 mm) were compared. They found that subsurface drip irrigation can mitigate N_2O emissions compared to drip irrigation. However, another study showed a negligible impact on N_2O emissions when tomatoes were irrigated comparing surface drip and subsurface drip irrigation systems [67]. A cotton study in China showed that drip irrigation, which uses less water than furrow irrigation could significantly decrease N_2O emissions when combined with certain management practices. Drip irrigation with a plastic film mulching decreases N_2O emissions by 36% compared to the furrow irrigation, which is mulch-free [59]. N_2O emissions were also reduced in a rapeseed study performed in China in a sandy loam soil [88]. In the study, continuous flooding, which uses the highest amount of irrigated water in the irrigation methods compared had the highest N_2O emissions (12.05 kg N_2O ha^{-1}) while rain-fed plots with limited irrigation had the lowest emission (8.31 kg N_2O ha^{-1}). In contrast, the same study reported opposite findings in case of rice paddy cultivation, where continuous irrigation yielded the lowest N_2O emissions (6.76 kg N_2O ha^{-1}) compared to the other two irrigation treatments—flooded and wet intermittent (8.44 kg N_2O ha^{-1}) and rainfed with limited irrigation (11.28 kg N_2O ha^{-1}) [88].

Cover crop is commonly used as a method to retain soil moisture but has clear effects on GHG emissions as reported by Kallenbach et al. [73]. In that study, they showed that N_2O emission from tomato fields is dependent on both use of cover crop and irrigation method, where N_2O emissions remained lower from subsurface drip irrigated fields compared to furrow irrigated except for during rain events under cover crop treatment. Though these studies demonstrate that decreasing the total volume of water applied to soils generally leads to lower N_2O emissions in irrigated fields, the frequency of irrigation can greatly determine whether N_2O emissions increase or decrease upon implementing deficit irrigation. For example, increase in N_2O emissions (up to 4.5 kg N_2O ha^{-1}) was observed in studies that applied intermittent irrigation as compared to traditional irrigation or continuous flooding [65,72,77,83,86–88,91]. Similarly, a number of studies demonstrated that continuous flooding leads to lower N_2O emissions as compared to water-saving irrigation treatments in studies done in China, South Korea, and the USA [57,64,71,76,84,85].

3.2. Effects of Irrigation on CO_2 Emissions

Many studies reviewed did not report CO_2 emissions from different irrigation treatments. Only fifteen studies reported CO_2 emissions and are presented in Table 1. A majority of studies either showed a significant increase in CO_2 emissions with reduced amounts of irrigation or reported non-significant effects regardless of irrigation treatments. Only two studies reported a significant decrease in CO_2 emissions with lower amount of irrigated water applied or with a change in irrigation strategies. Studies that compared surface drip irrigation and subsurface drip irrigation systems in Canada found negligible effect on CO_2 emissions [67]. Similar non-significant findings were reported by Maris et al. [78] in Spain when they evaluated the effect of surface drip and subsurface drip irrigation on the CO_2 emissions. Franco-Luesma et al. [70] also did not find a significant effect of irrigation treatments in the CO_2 emissions when they compared two irrigation treatments-high frequency (2090 kg CO_2 ha^{-1}) and low frequency (2050 kg CO_2 ha^{-1}).

Significant increase in CO_2 emissions were observed mostly in rice paddy studies when continuous flooding was compared with intermittent drainage or flooding. In a study by Haque et al. [71], the average CO_2 emissions were significantly increased by 47% in a mid-season drainage treatment compared to continuous flooding. A similar increase (19%) in CO_2 emissions was reported by Haque et al. [72] in another study when they compared continuous flooding and intermittent drainage. Intermittent flooding in paddy fields significantly increases CO_2 emissions by up to 95% in a number of studies performed in China and Spain [77,84,87]. Tillage also played a major role in increasing CO_2 emissions. A study done by Fangueiro et al. [68] in Spain did not find significant differences in CO_2 emissions from flood versus sprinkler irrigation when paddy was grown under no-tillage conditions. However, the average CO_2 emissions significantly increased (53%) under sprinkler irrigation systems than in the flood irrigation under tillage. The sprinkler irrigation system was a water-saving strategy, which uses only 700 mm of irrigated water during the growing season while the flood irrigation treatments utilized 2300 mm of irrigated water [68]. This finding was supported by Tang et al. [83] who found that under tillage, either 1-yr tillage or 57-yr old tillage, intermittent irrigation significantly increases mean CO_2 emissions up to 27% compared to continuous flooding. Similarly, Kallenbach et al. [73] showed that though deficit irrigation (subsurface drip) alone did not significantly affect CO_2 flux, use of winter legume cover crop increased CO_2 emissions dramatically with furrow irrigation.

A study that reported a significant decrease in CO_2 emission because of intermittent irrigation was discussed by Riya et al. [79], where CO_2 emission in the intermittent irrigation treatment was 40% less (6,169 kg CO_2 ha^{-1}) than compared to emissions from continuously flooded plots. A 2-yr study done by Kumar et al. [74] in eastern India also found a significant decrease in CO_2 emissions through reduced application of irrigation water. In the study, the effect of continuous flooding and five other irrigations (−20 kPa, −30 kPa, −40 kPa, −50 kPa, and −60 kPa) applied based on soil water potential were assessed. Irrigations that had higher soil water potential (−40 to −60 kPa; treatments using less irrigation water), compared to the treatments where higher amounts of water was applied, yielded significantly lower CO_2 compared to continuous flooding, where CO_2 emission was up to 117 kg CO_2 ha^{-1} less than the continuous flooding.

3.3. Effects of Irrigation on CH_4 Emissions

Methane emissions from agricultural fields with different irrigation rates were reported in 27 studies (Table 1). Twenty-five of the 27 studies showed that a reduced rate of irrigation with water saving strategies decreases the rate of CH_4 emission as compared to traditional or flood irrigation. This includes upland crop studies that showed that the soil acted better as a methane sink under reduced irrigation than higher volume applications. For example, a study performed on cotton crops grown in heavy loam soils of Xinjian, China, showed that soils acted as a CH_4 sink under both furrow and drip irrigation, and that the degree of sequestration was dependent on season. Under drip irrigation, larger soil CH_4 uptake was observed than in furrow-irrigated fields (−2.92 kg CH_4 ha^{-1} under furrow irrigation versus −8.87 kg CH_4 ha^{-1} under drip-irrigation) [59]. Similarly, CH_4 emissions reduced up to 350 kg CH_4 ha^{-1} in a loam soil in Spain when sprinkler irrigation was applied to the paddy field instead of flood irrigation [68]. In summary, CH_4 emissions were lowered (Table 1) in reduced or intermittent irrigation treatments compared to emissions from high or continuous flood irrigation treatments. The only study that showed an increase in CH_4 emissions due to reduced irrigation was in Wang et al. [84]. In this study, three different irrigation treatments including flood, surface drip, and sprinkler irrigation were applied in a wheat study grown in a sandy loam soil. In contrast to all other studies reviewed, Wang et al. showed that CH_4 emissions increased when sprinkler irrigation was applied as compared to flood irrigation; however, CH_4 emissions were lower when surface drip irrigation was compared with flood irrigation [84].

3.4. GHG Emissions and Global Warming Potential

Overall, the effect of irrigation strategies had inconsistent effects on N_2O emissions, though in most cases continuous irrigation lead to the lower N_2O emissions compared to intermittent or water saving irrigation strategies. The effect of irrigation strategies on GWP (taking only N_2O + CH_4 into account) shows that reduced or deficit irrigation has a potential to reduce GHG emission impact. Out of all the studies that were used to calculate GWP (N_2O + CH_4), only one study showed an increase in GWP by 6% [80]. Similarly, when $GWP_{(N_2O + CH_4 + CO_2)}$ was calculated using all three GHGs whenever reported, three studies out of eleven showed an increased GWP when reduced irrigation was used. Since CO_2 emission was very high for low or reduced or intermittent irrigation in these studies [75,77,83], increased CO_2 emissions had a large impact on its net GWP [75]. Otherwise, all other studies had lower $GWP_{(N_2O + CH_4)}$ or $GWP_{(N_2O + CH_4 + CO_2)}$ for reduced or deficit or intermittent irrigation compared to continuous flooding.

4. Discussion

In the following discussion, we provide a number of mechanistic explanations for how irrigation rate and volume control the flux of the three GHGs, while also providing insight into how redox processes likely play a key role in determining whether GHG emissions are enhanced or suppressed under different irrigation practices.

4.1. N_2O Emissions and Irrigation Treatments

Use of synthetic nitrogen fertilizers and animal manure to enhance crop yields has contributed to a large increase in atmospheric N_2O concentrations (0.3 Tg N_2O-N yr^{-1}) emitted during the preindustrial period (1860s) to 3.3 Tg N_2O-N yr^{-1} during the last decade (2007–2016) [92], making agricultural N_2O emissions the greatest anthropogenic contributor to global N_2O emissions [92,93]. Though application of N fertilizer has been found to control the N_2O producing potential of managed lands, irrigation rate controls the extent to which that potential is reached and can, therefore, be leveraged to minimize

N_2O flux from croplands [94,95]. The variable rate of N_2O emissions in studies included in this review were found to be associated with differences in irrigation frequency; that is, it is important to consider the temporal variation in water application in addition to the total volume of water applied when evaluating how to decrease soil N_2O emission.

The studies indicate that less frequent irrigation events lead to lower N_2O emissions, though the amount is dependent upon local climate. A likely mechanism for this trend is that less frequent water application allows more time for oxygen to penetrate into the soil matrix between irrigation events, which would favor microbial nitrification; when soil water content is low enough, these factors lead to a suppression of all microbial activity in the soil and hence an overall decrease in N_2O emission [7]. On the other hand, flood irrigation including furrow will promote anoxic processes including N_2O production through denitrification. Aside from lowered irrigation rate as a cause for decreased N_2O emissions [68,81]; decrease in N_2O emissions can also be caused by soil aeration [84], though aeration effects on N_2O production is highly dependent on soil moisture content [96], where microbial nitrification is then water-limited under arid conditions instead of O_2-limited. Finally, water delivery was recently demonstrated to also contribute to differences in N_2O emissions from irrigated fields [97]. By comparing flood irrigation to sprinkler and drip irrigation, researchers determined that the hydrologic forms (irrigation or flooding frequency, timing, and duration) will cause contrasting GHG emission patterns [98]. Specifically, large volumes of soil pores are water-filled completely and simultaneously during furrow or flood irrigation, which leads to a singular large pulse in N_2O release from wetted soils; whereas low volume methods, such as sprinkler and drip irrigation, leave a large volume of unfilled pores or partially filled pores, causing more variable and generally less intense pulses of N_2O emissions [96].

Studies, including Ali et al. [65], Xu et al. [87], and Xu et al. [88], showed that intermittent irrigation increased N_2O emission compared to continuous flooding. A commonality in these studies is that paddies were cultivated during the field experiments, during which irrigation rates were temporarily decreased, essentially leading to soil conditions that are similar to those that result under an intermittent irrigation regime. These field observations are supported by ex situ incubation studies that imposed alternating aerobic (aeration with O_2) and anaerobic (bubbling with N_2) conditions in soil slurries, which suggested that soils under fluctuating moisture conditions are likely to emit more N_2O than the soils under continuously well-aerated or excess-moisture conditions [99].

Overall, there is a paucity of studies that compare GHG flux from multiple (greater than two) irrigation systems such as a single study inclusive of flood, sprinkler, and drip irrigation. However, based on the studies reviewed here, the maximum N_2O flux from flood irrigated fields was higher (18 kg N_2O ha^{-1}) [88] than the maximum flux from sprinkler or drip systems (7.95 kg N_2O ha^{-1}) [68]. This summary of study findings demonstrates that the emission of N_2O as a function of irrigation frequency and volume results in occasionally contradictory findings across experiments. However, in general, it appears to be consistent that studies that allowed soils to undergo both oxic and anoxic conditions during the growing season triggered greater cumulative N_2O production, likely due to favoring contribution of N_2O production from both aerobic nitrification and anaerobic denitrification processes. Low volume or less frequent irrigation allows for maximum aeration, which favors aerobic respiration over denitrification. However, intermittent irrigation that is more frequent may favor nitrate respiration by poising the redox potential just below the threshold for aerobic respiration. Similarly, irrigation in extremely arid regions showed greatest N_2O production with high volume irrigation methods, but N_2O production in such regions is particularly sensitive to fertilizer input [100].

4.2. CO_2 Emissions and Irrigation Treatments

Results included in this review (Table 1) collectively showed that CO_2 emission from continuously flooded cropping systems were suppressed compared to systems with reduced or intermittent irrigation. In all studies that reported CO_2 flux, greater rate of emissions was attributed to increased aeration of soils when reduced irrigation was applied compared to flood irrigation. Additionally, reduced rainfall was shown to increase dependency on rainwater, which can have created aerobic conditions that favored soil organic matter decomposition enhancing soil CO_2 production [88]. There are physical factors that likely contribute to this trend, such as slowed gas release from diffusion limitations when pores are inundated in continuous flood systems [101] versus gas flux pulses that may result from soil cracking to form preferential flow paths [102], which can form during water-stressed condition in fine textured soils [68,73,103]. A number of other physical factors that cause sudden pulses of CO_2 can also confound our understanding of irrigation impacts on C turnover particularly within field-based studies; management practices that disturb soil structure such as tillage, planting of cover crops, and incorporation of residuals can cause high peaks of CO_2 from release of subsurface accumulated CO_2 [68]. These disturbances will then increase oxygen availability in the soil matrix, which stimulates microbial degradation of organic carbon [104–106].

Incorporation of cover crop residues is commonly used as a method to improve soil structure and increase soil organic carbon [107,108]; however, residue incorporation can lead to greater CO_2 and N_2O emissions because of enhanced supply of organic matter in surface soils that are well aerated. Haque et al. [72] demonstrated that the incorporation of cover crop into paddy soils leads to a general increase in all three GHGs under both continuous flooding and intermittent drainage of rice paddies compared to treatments without residue incorporation. However, as expected CO_2 emission rates were greatest with intermittent drainage, as soil redox potential shifted from highly reducing to highly oxidizing.

Temperature is another variable that controls the overall rate of soil GHG emissions that was examined in a number of studies reviewed, namely that increased temperatures can increase microbial respiration rates, which enhanced gas flux until temperatures are high enough that low water availability becomes the rate-limiting factor. When examining the effect of temperature and water availability on winter wheat, Li et al. [75] showed that regardless of irrigation rate, winter wheat in a semi-arid zone sandy loam exhibited higher CO_2 emissions during warming treatments, which were particularly sensitive during winter seasons. Warming events leads to increased root biomass and litter deposition, which then stimulates microbial activity when sufficient soil water is available [109,110]. A similar dominating effect of temperature was seen controlling CO_2 emissions from winter wheat under three irrigation methods [84,111].

4.3. CH_4 Emissions and Irrigation Treatments

Overall, studies consistently showed that CH_4 emissions decreased drastically under both reduced volume and frequency of irrigation water applied. Correspondingly, results collectively showed that full or continuous flood irrigation systems yielded greater total CH_4 emission compared to intermittent or reduced irrigation. Globally, contribution of rice production to methane emissions has been the focus of many studies, where a past estimate reported that 9%–19% of methane emissions is sourced from rice paddies [112] and that rice has the highest global warming potential of among major cereal crops [113]. This fact is reflected in this review as a majority of studies included here provided information regarding the effect of deficit irrigation on CH_4 were performed on rice paddy systems. Previous studies have demonstrated that reduced irrigation practices can lower CH_4 emissions while maintaining rice yields [114–117]. More than two decades ago, a large number of rice production operations in China had shifted from continuous flood to application of mid-season drainage [118]. A comparison between the emissions from continuously flooded rice paddies to adding mid-season drainage, a method used to reduce water use, lead to a drastic decrease in methane production of up to 80% in some studies [119–122]. In a meta-analysis by Yan et al. [116], it was determined that water regime and organic amendments were the two major controlling factors of CH_4 release from rice fields, where the addition of rice straw could increase emissions by over 200%.

Changes in methane emissions upon shifts in water regimes have been explained through changes in redox potential and microbial activity within the soil matrix [123]. When fields are continuously flooded, reducing conditions quickly ensue particularly with organic amendments providing additional electron donors that can be used to exhaust any remaining dissolved oxygen. As anaerobic conditions arise, soil microbes respire upon alternative electron acceptors including iron and manganese oxides, sulfate, and CO_2, producing Fe(II), Mn(II), sulfide, and methane, respectively. When alternate wetting and drying (AWD) or intermittent drainage methods are applied to previously flooded fields, aeration allows for the reoxidation of the reduced species. Abiotic oxidation of Fe^{2+} to Fe(III) oxides is relatively fast compared to microbially-mediated methane oxidation. Therefore, as Fe(III) oxides are precipitated in the drained or aerated soils that were previously flooded, these oxides provide an alternate electron accepting source for respiration that competes with and decreases the rate of methanogenesis due to Fe(III) being an energetically more favorable electron acceptor [124]. It has also been shown that the thermodynamic favorability of anaerobic respiration processes is highly dependent upon the chemical composition of the organic carbon sources, which microbes are utilizing as electron donors [125], where carbon compounds with nominal oxidation states below a certain threshold become energetically unfavorable to utilize. Therefore, aside from aeration providing additional alternate electron acceptors to suppress methanogenesis, the complexity of carbon added from organic amendments will also dictate likelihood and rate of methane production.

5. Conclusions

By comparing across all results from studies included in this review, it was generally seen that CO_2 emissions increase and CH_4 emissions decrease when reduced irrigation is applied to croplands, whereas the extent of N_2O emission was widely variable between irrigation treatments. A large majority of the studies included in this review have paddy/rice as the major crop under examination based on the search criteria, which was focused towards synthesizing findings from field-based agricultural studies linking irrigation method and GHG production. Within this context, the major findings from this review are that, CH_4 emissions and GWP can be decreased by applying reduced irrigation water. Decreasing emissions through effective water and irrigation management can therefore aim to reduce GHG emissions globally. As noted in this review, there is still a lack of studies that investigate multiple irrigation strategies within a single field-based experiment, which would aid in better comparing across irrigation types. However, such examinations are time and resource intensive and, therefore, more accessible and affordable high-throughput analytical methods may be required to facilitate such field experiments in the future. Many agricultural based studies have traditionally been designed as a large factorial experiment, where a large matrix of control and test plots are monitored. However, such studies are sometimes difficult to extract mechanistic understanding of underlying controlling processes that drive GHG production and, therefore, could benefit from being paired with additional smaller scale field or lab-based studies specifically probing potential biogeochemical mechanisms.

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