Nature Environment and Pollution Technology
An International Quarterly Scientific Journal
p-ISSN: 0972-6268 (Print copies up to 2016)
e-ISSN: 2395-3454
Vol. 21 | No. 4 | pp. 1697-1703 | 2022
Review Research Paper
https://doi.org/10.46488/NEPT.2022.v21i04.023
Open Access Journal

Nitrous Oxide Emissions Generated in Coffee Cultivation: A Systematic Review

L. Quiñones-Huatangari*†, F. H. Fernandez-Zarate and A. E. Huaccha-Castillo*(***)**
*Instituto de Ciencia de Datos, Universidad Nacional de Jaén, Cajamarca, Perú
**Facultad de Ciencias Agrarias, Universidad Nacional Autónoma de Chota, Cajamarca, Perú
***Ingeniería Forestal y Ambiental, Universidad Nacional de Jaén, Cajamarca, Perú
†Corresponding author: L. Quiñones-Huatangari; lenin.quinones@unj.edu.pe

Nat. Env. & Poll. Tech.
Website: www.neptjournal.com

Received: 19-01-2022
Revised: 08-03-2022
Accepted: 10-03-2022

Key Words:
Greenhouse effect
Climate change
Nitrous oxide emissions
Coffea arabica

ABSTRACT

The objective of the research was to provide an overview of soil N_2O emissions in coffee cropping systems; summarizing available field data on soil emissions and identifying controlling factors (fertilizer type, precipitation, temperature, altitude). A systematic search of Scopus, Science Direct, Springer, and Scielo for experimental-type studies was conducted from January 2000 to October 2021. Of the seventy manuscripts determined through the search strategy, eight studies met the inclusion criteria. Analysis of the included studies revealed that they were conducted in Ecuador, Costa Rica, and Nicaragua; the rainfall of the fields ranged from 910 mm to 2740 mm per year and the average temperature was 20.3°C. Coffee is planted under agroforestry systems and monocultures; in addition, the most abundant forest species in coffee agroforestry systems are leguminous plants of the Inga and Erytrina genus and 60% of the studies have been developed with the Catuai coffee variety. The pH and humidity of the soil where coffee plantations are developed range from 4.67 to 6.34 and 53.3 to 67.05% respectively. Finally, the fertilizers used are of chemical, organic, and chemical + polymer origin, at fertilization rates ranging from 66 to 400 $kg.N.ha^{-1}yr^{-1}$ and N_2O emissions ranging from 0.2 to 12.8 $kg.N.ha^{-1}yr^{-1}$. Overall, the present systematic review provides a scientific basis for evaluating N_2O emissions generated in coffee crops.

INTRODUCTION

Agriculture is responsible for 10 to 12% of total greenhouse gas (GHG) emissions, 52% of N_2O, 18% of CO_2 and 84% of CH_4 (IPCC 2014), the increase in the atmospheric concentrations of these gases generates global warming (Guo et al. 2021). Coffee is the most traded tropical agricultural product worldwide, its cultivation thrives in more than 50 countries and covers an area of more than 11 million hectares (Davis et al. 2012, De Beenhouwer et al. 2015), due to population growth and increased demand for this product, GHG emissions from these agricultural ecosystems tend to continue to increase (Wang et al. 2021). The increase of coffee monoculture systems in Latin America has led to the application of a high rate of mineral fertilizers to improve the productivity and profitability of these plantations (Romero-Alvarado et al. 2002); however, the excessive use of these inputs by coffee growers generates several environmental problems (Capa et al. 2015), for example, eutrophication (Borbor-Cordova et al. 2006), reduction of soil microorganism biodiversity (De Beenhouwer et al. 2015), GHG emissions (Hergoualc'h et al. 2012, Hergoualc'h et al. 2008). Maintaining or increasing crop productivity while reducing GHG emissions is one of the major challenges facing agriculture (Lesk et al. 2016).

N_2O is a long-lived GHG in the atmosphere, whose global warming potential is 298 times that of CO_2 (Forster et al. 2007), is mainly emitted in agricultural soils fertilized with nitrogen (Recio et al. 2020) and is the substance that has the greatest effect on the destruction of stratospheric ozone (Ravishankara et al. 2009). Both nitrification and denitrification are considered to be the main biological processes leading to N_2O emission in agroecosystems (Butterbach-Bahl et al. 2013, Recio et al. 2020). Nitrification generally occurs under aerobic conditions, while denitrification occurs under oxygen-deficient conditions, although the two processes often occur simultaneously when there is a close coexistence of oxic and anoxic conditions (Baggs & Philippot 2011, Hallin et al. 2018). These two processes are favored by the amount of soil water (water-filled pore space, WFPS) under saturation (40-60% WFPS) (Sanz-Cobena et al. 2017).

Different N_2O emission reduction strategies have been established in nitrogen-fertilized agroecosystems (Sanz-Cobena et al. 2017), these include the synchronization of the N applied with the N demand of the crop, the use of water-saving irrigation systems to prevent N_2O formation through denitrification in water-saturated soils, and the use of water-saving irrigation systems to prevent the formation of N_2O through denitrification in water-saturated soils (Guardia et al. 2017) or application of nitrification inhibitors (NI) (Sanz-Cobena et al. 2016). The most commonly used INs are dycyandimide (DCD) and 3,4-dimethylpyrazole phosphate (DMPP) which have demonstrated a high potential to decrease nitrifying activity and consequently decrease N_2O emissions (Cayuela et al. 2017, Lam et al. 2018).

Systematic reviews (SR) is a useful and comprehensive technique to search, collect, select, evaluate and synthesize all the existing evidence on a specific problem, this method suggests key features, including the development of a thorough search and coding method, analysis-interpretation, and systematic reporting (Bai et al. 2022). Recently, several SR studies on GHG emissions have been reported (Gao et al. 2018, Guardia et al. 2017, Hu et al. 2020, Lynch 2019); however, there are no such studies focused on N_2O emissions in coffee cultivation. The objective of this SR was to provide an overview of soil N_2O emissions in coffee cropping systems; summarizing available field data on soil N_2O emissions and identifying N_2O control factors (fertilizer type, precipitation, temperature, altitude) as a basis for developing N_2O mitigation strategies.

MATERIALS AND METHODS

Search Strategy

The Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines were followed for the literature search and review (Moher et al. 2014). Duplicate articles were eliminated, then all titles and abstracts were evaluated following the inclusion and exclusion criteria to identify relevant research for the present review, after which full-text articles were reviewed to determine whether they met the inclusion criteria according to the research objective.

The databases used in the search for articles were Scopus, ScienceDirect, Springer, and Scielo. The keywords used were "nitrous oxide" and "coffee monoculture" or "nitrous oxide" and "coffee agroforestry systems" or "carbon footprint" and "coffee cultivation" o "óxido nitroso" y "café". All original full-text articles in English or Spanish, published from January 2000 to October 2021, were considered for review. To increase the quality of the review, only peer-reviewed literature was examined and results published in the form of master's theses, Ph.D. dissertations, and conference abstracts were excluded.

Inclusion and Exclusion Criteria

Inclusion criteria for the selection of articles were a) research studies conducted in the field; b) studies measuring cumulative emissions ($kg.ha^{-1}$) of N_2O; c) means, standard deviations (or standard errors), and several replicates that were reported, and/or could be calculated; d) experimental duration, N application rate and management practices that were reported. All study designs had to correspond to primary studies, including randomized controlled trials, crossover, cohort, case-control, case reports, and case series.

The following criteria were used to exclude articles (a) studies with a secondary design, such as meta-analyses, systematic reviews, and narrative reviews; (b) non-experimental studies; (c) studies in which other greenhouse gases were estimated; (d) articles without full text available; (e) studies whose object of research is other than N_2O emissions in coffee crops; (f) opinion articles, commentaries, and editorials were not considered for inclusion.

RESULTS AND DISCUSSION

Selection of Research Articles

A total of 70 articles were identified across the four databases and 10 articles were excluded due to duplication. Of that number, 46 articles were excluded after the first review of the title and abstract as it was determined that they did not meet the inclusion criteria. Next, 14 articles were evaluated by reading the full text to certify that they met all inclusion and exclusion criteria. Finally, the total number of studies included in the present systematic review was eight (Fig. 1).

Analysis of Included Studies

Table 1 shows the eight selected papers, indicating the country in which the study was carried out, as well as the precipitation, temperature, and altitude of the study areas.

Of the studies found, 75% were developed in Costa Rica, 12.5% in Ecuador, and the other 12.5% in Nicaragua. The range of precipitation reported in the RS goes from 910 mm to 2740 $mm.yr^{-1}$. Coffee is planted in areas with rainfall ranging from 750 mm to 3000 mm per year (Laderach et al. 2011). Precipitation is the climatic factor with the greatest impact on the decrease in coffee production (Rivera Silva et al. 2013), the reduction of rainfall in relation to the reduction of coffee productivity is estimated at 75-90% (Laderach et al. 2011).

The minimum temperature reported in the SR was 16°C, the maximum temperature was 24°C and the average temperature was 20.3°C. These values are within the optimal temperature range for coffee cultivation, which establishes the average temperature between 18 and 22°C and the maximum temperature of 30°C (Descroix & Snoeck 2009, Sarmiento-Soler et al. 2019), higher temperatures accelerate

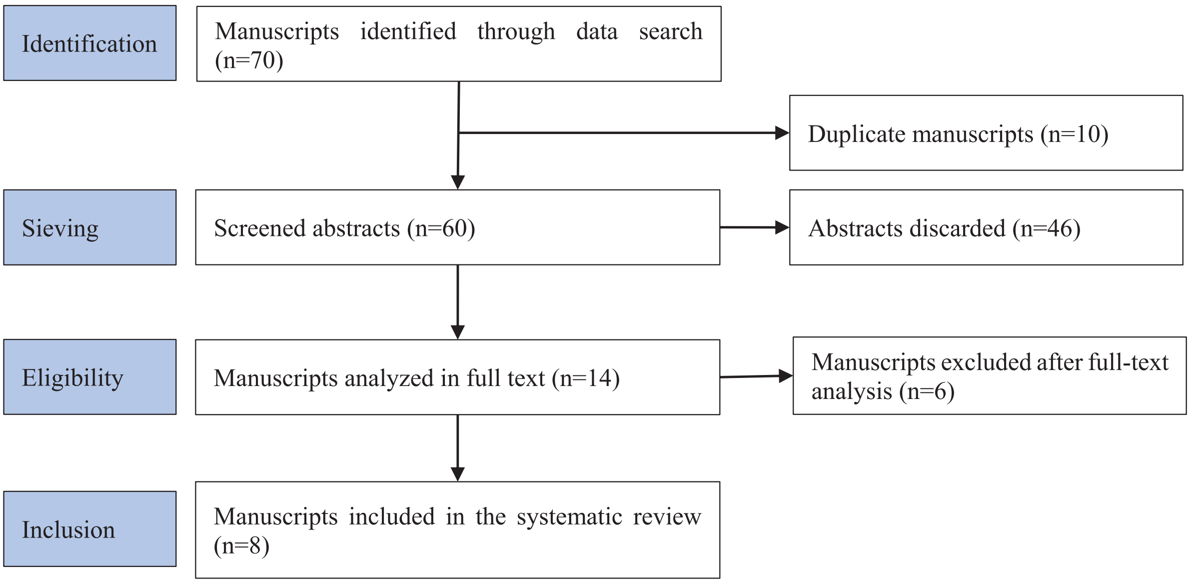

Fig. 1: Eligible item identification flowchart.

the development and maturation of the fruits and this leads to a decrease in the cup quality of the coffee, in addition, continuous exposure to high temperatures generates stress, which is manifested by slow growth and abnormalities such as yellowing of the leaves (Davis et al. 2012) similarly, in areas where the average annual temperature is below 17-18°C, growth also becomes slower (DaMatta & Ramalho 2006). Climatic characteristics influence the development and growth of coffee in different ways and at different stages of growth (Camargo 2010).

As for N_2O emissions, they increase with increasing temperature; in general, there is a positive correlation between temperature and N_2O emissions (Aguilera et al. 2013) the optimum range for nitrification is between 25 and 30°C, while denitrification can occur in a range between 4 and 60°C. In addition, the increase in temperature produces an increase in soil respiration, which leads to O_2 consumption and the appearance of anaerobiosis, which in turn favors denitrification (Ussiri & Lal 2012). In addition, the amount and distribution of precipitation influence soil N_2O emissions (Du et al. 2006).

Table 2 details aspects such as the coffee cultivation system, associated forest species, variety, age, and the number of coffee plants per ha.

In the SR it was found that coffee is planted under agroforestry systems and monocultures, however, coffee has a variety of cultivation systems, from complex agroforestry,

Table 1: Climatic and location conditions in which the selected studies were carried out.

Author and year of publication	Country	Altitude (msnm)	Precipitation (mm)	Average temperature (°C)
Capa et al. (2015)	Ecuador	2100	910	18
Harmand (2007)	Costa Rica	600	2740	23
Hergoualc'h et al. (2008)	Costa Rica	1180	2300	21
Hergoualc'h et al. (2012)	Costa Rica	1180	2300	21
Montenegro (2019)	Costa Rica (Naranjo)	1200	2200	21
Montenegro (2019)	Costa Rica (San Marcos)	1650	2223	16
Montenegro (2020)	Costa Rica (Naranjo)	1200	2200	21
Montenegro (2020)	Costa Rica (San Marcos)	1650	2223	16
Noponen et al. (2012)	Costa Rica	685	2600	22
Noponen et al. (2012)	Nicaragua	445	1386	24

Table 2: Characteristics of the cultivation system installed in each selected studio.

Author and year of publication	Crop system	Associated forest species	*Coffea arabica* variety	Age of the coffee crop (years)	Number of coffee plants per ha
Capa et al. (2015)	Monoculture	-	Caturra	1	5000
Harmand (2007)	Agroforestry system	*Eucalyptus deglupta*	Costa Rica 95	14	5900
	Monoculture	-	Costa Rica 95	14	5900
Hergoualc'h et al. (2008)	Agroforestry system	*Inga densiflora*	Catuai	8	4722
	Monoculture	-	Catuai	8	5000
Hergoualc'h et al. (2012)	Agroforestry system	*Inga densiflora*	Catuai	7	4722
	Monoculture	-	Catuai	7	4722
Montenegro (2019)	Agroforestry system	*Inga* spp, *Erytrina* spp	Catuai	7	5848
	Agroforestry system	*Inga* spp, *Erytrina* spp	Catuai	15	5848
Montenegro (2020)	Agroforestry system	*Inga* spp, *Erytrina* spp	Catuai	7	5848
	Agroforestry system	*Inga* spp, *Erytrina* spp	Catuai	15	5848
Noponen et al. (2012)	Agroforestry system	*Erythrina poeppigina*	Caturra	9	5000
	Agroforestry system	*Inga laurina*	Pacas	9	4000

simulating secondary forests, to intensive monocultures (Perfecto et al. 2005), choosing a particular cropping system is a very important management decision because cropping systems will provide different benefits, e.g. nutrient regulation, pest control, microclimate regulation, pollination and productivity (Chain-Guadarrama et al. 2019, Padovan et al. 2018). Coffee planted under agroforestry systems may be affected, reducing its productivity (Franck et al. 2007, Vaast et al. 2006) however, it provides a variety of ecosystem services (Perfecto et al. 2005), on the other hand, coffee planted as a monoculture and using high fertilization rates can achieve high yields (DaMatta et al. 2018, Perfecto et al. 2005). The most abundant forest species in coffee agroforestry systems are leguminous plants of the genus *Inga* and *Erythrina* (Cannavo et al. 2011) emissions, such as the data found in this SR. If we talk about N_2O emissions, these would increase in a coffee crop planted under an agroforestry system due to the higher amount of organic matter and water in the top layer of soil under the trees (Hergoualc'h et al. 2008, Verchot et al. 2006).

In the last decades, this variety has been replacing older varieties of coffee due to its productivity, especially in Central America, and in the last decades, the Catuai variety has been replacing older varieties of coffee (Hergoualc'h et al. 2008).

Table 3 shows the edaphic characteristics of the areas where the studies included in this SR were carried out. In the SR it was found that the pH and humidity of the soil where the coffee plantations are developed range from 4.67 to 6.34 and 53.3 to 67.05% respectively, these properties influence N_2O emissions. N_2O emissions are the product of microbial processes that in turn are controlled by physical and chemical properties of the soil that influence the growth of microorganisms, among these properties are texture, availability of oxygen (O_2), organic C, mineral N, moisture, and pH (Müller et al. 2014). Soil moisture has a considerable influence on N_2O production, due to its relationship with the concentration of oxygen O_2 in the soil, the higher the water content, the lower the O_2 content in the soil pores, when the percentage of water-filled pores (WFPS) is between 50 and 70% and decreases to values below 50% or above 80%, the process of complete denitrification predominates, therefore, the reduction of N_2O to N_2O is more

Table 3: Edaphic conditions in which the selected studies were conducted.

Author and year of publication	pH	Soil humidity [%]	Texture
Capa et al. (2015)	6.34	-	Clay loam
Harmand (2007)	6.2	53.3	Sandy
Harmand (2007)	6.1	53.3	Sandy
Hergoualc'h et al. (2008)	4.67	62.95	Clay
Hergoualc'h et al. (2008)	4.92	67.05	Clay
Hergoualc'h et al. (2012)	4.67	-	Clay
Hergoualc'h et al. (2012)	4.92	-	Clay
Montenegro (2019)	5	60	Clay loam
Montenegro (2019)	5	55	Clay
Montenegro (2020)	5	60	Clay loam
Montenegro (2020)	5	55	Clay
Noponen et al. (2012)	-	-	Clay
Noponen et al. (2012)	-	-	Sandy loam

Table 4: Nitrogen fertilization and calculated N_2O emissions in selected studies.

Author and year of publication	Fertilizer type	Fertilization rate [$kg.N.ha^{-1}$]	Emissions N_2O [$kg.N.ha^{-1}.yr^{-1}$]
Capa et al. (2015)	Urea	200	2.90
	Urea	300	10.90
	Urea	400	12.80
	Control	0	1.30
Harmand (2007)	Ammonium nitrate	180	1.90
	Ammonium nitrate	180	1.90
Hergoualc'h et al. (2008)	Urea	250	5.80
	Urea	250	4.30
Hergoualc'h et al. (2012)	Urea	250	3.55
	Urea	250	2.32
Montenegro (2019)	Urea	0	0.63
	Urea	100	0.95
	Urea	225	0.95
	Urea	350	1.40
	Urea	0	0.63
	Urea	100	0.83
	Urea	225	1.00
	Urea	350	1.07
Montenegro (2020)	Ammonium nitrate	250	1.00
	Calcium nitrate	250	0.94
	Polymer coated urea	250	0.87
	Urea	250	0.67
	Ammonium nitrate	250	0.65
	Calcium nitrate	250	0.60
	Polymer coated urea	250	0.65
	Urea	250	0.57
Noponen et al. (2012)	Moderate organic	66	0.20
	Intensive organic	248	1.56
	Conventional moderate	150	1.02
	Conventional intensive	287	1.87
	Moderate organic	140	0.37
	Intensive organic	346	1.83
	Conventional moderate	78	0.49
	Conventional intensive	157	0.95

important (Pilegaard 2013). In addition, denitrification and nitrification processes are affected by other soil physical and chemical parameters such as pH, temperature, and the presence of other species. Soil pH has been recognized as an important property controlling N_2O emissions through its effect on soil microbial activity and diversity (Barton et al. 2013, Čuhel et al. 2010). At pH values close to 7 or basic, N_2 production is favored over N_2O emission (Šimek et al. 2002) which results in lower N_2O emissions (García-Marco et al. 2016) than at acid pH.

In addition, texture influences N_2O emissions, for example, in clay soils the number of macropores increases anaerobic zones, which leads to partial or total denitrification processes, resulting in higher N_2O emissions from fine-textured soils (Butterbach-Bahl et al. 2011). Table 4 details the type of nitrogen fertilizer used in the coffee crop, as well as the fertilization rate and N_2O emissions of the crop.

In the SR it was found that the fertilizers used are of chemical, organic and chemical + polymer origin, at fertilization rates ranging from 66 to 400 kg Nha^{-1} and N_2O emissions ranging from 0.2 to 12.8 $kg.N.ha^{-1}yr^{-1}$, it has been observed that N_2O emissions tend to increase as the fertilization rate does, as well as other studies, where they state that as the annual rate of N increases, so does the annual emissions of N_2O in soils (Capa et al. 2015, Hergoualc'h et al. 2008, Noponen et al. 2012, Rahman et al. 2021) which are mainly due to nitrification and denitrification processes generated by high rates of nitrogen fertilization (Rochette et al. 2004). In addition to this factor, N_2O emissions are due to environmental and agricultural factors, such as the presence of native mineral elements in the soil, soil moisture, temperature, type of tillage, and climatic conditions (Hergoualc'h et al. 2008).

CONCLUSION

The systematic review included eight experimental studies that determined N_2O emissions in coffee plantations, suggesting that this emission is directly proportional to the fertilization rate. The precise identification of the factors remains unclear. Further research is needed in this field to make recommendations to reduce N_2O emissions.

REFERENCES

Aguilera, E., Lassaletta, L., Sanz-Cobena, A., Garnier, J. and Vallejo, A. 2013. The potential of organic fertilizers and water management to reduce N_2O emissions in Mediterranean climate cropping systems. A review. Agric. Ecosyst. Environ., 164: 32-52.

Baggs, E. and Philippot, L. 2011. Nitrous Oxide Production in the Terrestrial Environment. Caister Academic Press, MA.

Bai, Z.G., Bing, Q., Gong, R.R., Bai, R.H., Zhou, Y. and Yang, K.H. 2022. Evidence-based social science in China: The quality of social science systematic reviews and meta-analysis published from 2000 to 2019. J. Clin. Epidemiol., 141: 132-140.

Barton, L., Gleeson, D.B., Maccarone, L.D., Zúñiga, L.P. and Murphy, D.V. 2013. Is liming soil a strategy for mitigating nitrous oxide emissions from semi-arid soils? Soil Biol. Biochem., 62: 28-35.

Borbor-Cordova, M.J., Boyer, E.W., McDowell, W.H. and Hall, C.A. 2006. Nitrogen and phosphorus budgets for a tropical watershed impacted by agricultural land use: Guayas, Ecuador. Biogeochemistry, 79(1): 135-161.

Butterbach-Bahl, K., Baggs, E.M., Dannenmann, M., Kiese, R. and Zechmeister-Boltenstern, S. 2013. Nitrous oxide emissions from soils: How well do we understand the processes and their controls? Phil. Trans. Royal Soc. B Biol. Sci., 368(1621): 20130122.

Butterbach-Bahl, K., Gundersen, P., Ambus, P., Augustin, J., Beier, C., Boeckx, P., Dannenmann, M., Sanchez Gimeno, B., Ibrom, A., Kiese, R., Kitzler, B., Rees, R. M., Smith, K.A., Stevens, C., Vesala, T. and Zechmeister-Boltenstern, S. 2011. Nitrogen Processes in Terrestrial Ecosystems. In Sutton, M., Howard, C.M., Erisman, J.W., Billen, G., Bleeker, A., Greenfelt, P., Grisnven, V.H. and Grizzetti, B. (eds), The European Nitrogen Assessment: Sources, Effects and Policy Perspectives. Cambridge University Press (CUP), Cambridge, MA, pp. 99-125.

Camargo, M.B.P. 2010. The impact of climatic variability and climate change on Arabic coffee crop in Brazil. Bragantia, 69: 239-247.

Cannavo, P., Sansoulet, J., Harmand, J.M., Siles, P., Dreyer, E. and Vaast, P. 2011. Agroforestry associating coffee and *Inga densiflora* results in complementarity for water uptake and decreases deep drainage in Costa Rica. Agric. Ecosyst. Environ., 140(1): 1-13.

Capa, D., Pérez-Esteban, J. and Masaguer, A. 2015. The unsustainability of recommended fertilization rates for coffee monoculture due to high N_2O emissions. Agron. Sustain. Dev., 35(4): 1551-1559.

Cayuela, M.L., Aguilera, E., Sanz-Cobena, A., Adams, D.C., Abalos, D., Barton, L., Ryals, R., Silver, W.L., Alfaro, M.A., Pappa, V.A., Smith, P., Garnier, J., Billen, G., Bouwman, L., Bondeau, A. and Lassaletta, L. 2017. Direct nitrous oxide emissions in Mediterranean climate cropping systems: Emission factors based on a meta-analysis of available measurement data. Agric. Ecosyst. Environ., 238: 25-35.

Chain-Guadarrama, A., Martínez-Salinas, A., Aristizábal, N. and Ricketts, T.H. 2019. Ecosystem services by birds and bees to coffee in a changing climate: A review of coffee berry borer control and pollination. Agric. Ecosyst. Environ., 280: 53-67.

Čuhel, J., Šimek, M., Laughlin, R. J., Bru, D., Chèneby, D., Watson, C. J. and Philippot, L. 2010. Insights into the effect of soil pH on N_2O and N_2 emissions and denitrifier community size and activity. Appl. Environ. Microbiol., 76(6): 1870-1878.

DaMatta, F.M., Avila, R.T., Cardoso, A.A., Martins, S.C.V. and Ramalho, J.C. 2018. Physiological and agronomic performance of the coffee crop in the context of climate change and global warming: A review. J. Agric. Food Chem., 66(21): 5264-5274.

DaMatta, F.M. and Ramalho, J.D.C. 2006. Impacts of drought and temperature stress on coffee physiology and production: A review. Braz. J. Plant Physiol., 18: 55-81.

Davis, A.P., Gole, T.W., Baena, S. and Moat, J. 2012. The Impact of Climate Change on Indigenous Arabica Coffee (*Coffea arabica*): Predicting Future Trends and Identifying Priorities. PLOS ONE, 7(11): e47981.

De Beenhouwer, M., Muleta, D., Peeters, B., Van Geel, M., Lievens, B. and Honnay, O. 2015. DNA pyrosequencing evidence for large diversity differences between natural and managed coffee mycorrhizal fungal communities. Agron. Sustain. Dev., 35(1): 241-249.

Descroix, F. and Snoeck, J. 2009. Environmental factors were suitable for coffee cultivation. Coffee: Growing, Processing, Sustainable Production. A Guidebook for Growers, Processors, Traders and Researchers, pp. 168-181.

Du, R., Lu, D. and Wang, G. 2006. Diurnal, seasonal, and inter-annual variations of N_2O fluxes from native semi-arid grassland soils of inner Mongolia. Soil Biol. Biochem., 38(12): 3474-3482.

Forster, P., Ramaswamy, V., Artaxo, P., Betts, R., Berntsen, T., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G. and Nganga, J. 2007. Climate change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change. Chap. Changes in Atmospheric Constituents and Radiative Forcing. UK and New York, NY, USA.: Cambridge University Press, Cambridge.

Franck, N., Vaast, P. and Dauzat, J. 2007. Coffee A Shade-Adapted Plant: Implications on Its Carbon Balance and Consequences on Coffee Yield and Quality in Agroforestry Systems. 21st International Conference on Coffee Science, Montpellier, France, 11-15 September 2006, 1023-1031.

Gao, J., Kovats, S., Vardoulakis, S., Wilkinson, P., Woodward, A., Li, J., Gu, S., Liu, X., Wu, H., Wang, J., Song, X., Zhai, Y., Zhao, J. and Liu, Q. 2018. Public health co-benefits of greenhouse gas emissions reduction: A systematic review. Sci. Total Environ., 627: 388-402.

García-Marco, S., Abalos, D., Espejo, R., Vallejo, A. and Mariscal-Sancho, I. 2016. No-tillage and liming reduce greenhouse gas emissions from poorly drained agricultural soils in Mediterranean regions. Sci. Total Environ., 56: 512-520.

Guardia, G., Cangani, M.T., Andreu, G., Sanz-Cobena, A., García-Marco, S., Álvarez, J.M., Recio-Huetos, J. and Vallejo, A. 2017. Effect of inhibitors and fertigation strategies on GHG emissions, NO fluxes, and yield in irrigated maize. Field Crops Res., 204: 135-145.

Guo, L.-N., She, C., Kong, D.B., Yan, S.-L., Xu, Y.P., Khayatnezhad, M. and Gholinia, F. 2021. Prediction of the effects of climate change on hydroelectric generation, electricity demand, and emissions of greenhouse gases under climatic scenarios and optimized ANN model. Energy Rep., 7: 5431-5445.

Hallin, S., Philippot, L., Löffler, F.E., Sanford, R.A. and Jones, C.M. 2018. Genomics and Ecology of Novel N_2O-Reducing Microorganisms. Trends Microbiol., 26(1): 43-55.

Harmand, J.M., Ávila, H., Dambrine, E., Skiba, U., de Miguel, S., Renderos, R.V. and Beer, J. 2007. Nitrogen dynamics and soil nitrate retention in a *Coffea arabica-Eucalyptus deglupta* agroforestry system in Southern Costa Rica. Biogeochemistry, 85(2): 125-139.

Hergoualc'h, K., Blanchart, E., Skiba, U., Hénault, C. and Harmand, J.M. 2012. Changes in carbon stock and greenhouse gas balance in a coffee (*Coffea arabica*) monoculture versus an agroforestry system with *Inga densiflora*, in Costa Rica. Agric. Ecosyst. Environ., 148: 102-110.

Hergoualc'h, K., Skiba, U., Harmand, J.M. and Hénault, C. 2008. Fluxes of greenhouse gases from Andosols under coffee in monoculture or shaded by *Inga densiflora* in Costa Rica. Biogeochemistry, 89(3): 329.

Hu, M., Sardans, J., Yang, X., Peñuelas, J. and Tong, C. 2020. Patterns and environmental drivers of greenhouse gas fluxes in the coastal wetlands of China: A systematic review and synthesis. Environ. Res., 186: 109576.

IPCC. 2014. Climate Change 2014-Mitigation of Climate Change: Working Group I Contribution to the Fourth Assessment Report of the IPCC. Cambridge University Press.

Laderach, P., Lundy, M., Jarvis, A., Ramirez, J., Portilla, E. P., Schepp, K. and Eitzinger, A. 2011. Predicted Impact of Climate Change on Coffee Supply Chains. In Leal Filho, W. (ed.), The Economic, Social and Political Elements of Climate Change. Springer, Berlin, Heidelberg, pp. 703-723.

Lam, S.K., Suter, H., Bai, M., Walker, C., Davies, R., Mosier, A.R. and Chen, D. 2018. Using urease and nitrification inhibitors to decrease ammonia and nitrous oxide emissions and improve productivity in a subtropical pasture. Sci. Total Environ., 644: 1531-1535.

Lesk, C., Rowhani, P. and Ramankutty, N. 2016. Influence of extreme weather disasters on global crop production. Nature, 529(7584): 84-87.

Lynch, J. 2019. Availability of disaggregated greenhouse gas emissions from beef cattle production: A systematic review. Environ. Impact Assess. Rev., 76: 69-78.

Moher, D., Liberati, A., Tetzlaff, J., Altman, D.G. and Group, T.P. 2014. Reference items to publish systematic reviews and meta-analyses: the PRISMA declaration. Rev. Espanola de Nutr. Hmm. Diet., 18(3): 172-181.

Montenegro, J. 2019. Respuesta polinómica de la emisión de óxido nitroso en plantaciones de café en Costa Rica. Rev. de Ciencias Amb., 53(2): 1-24.

Montenegro, J. 2020. Efecto de diferentes fuentes de nitrógeno en la emisión de óxido nitroso en plantaciones de café en Costa Rica. Rev. de Ciencias Amb., 54(2): 111-130.

Müller, C., Laughlin, R.J., Spott, O. and Rütting, T. 2014. Quantification of N_2O emission pathways via a 15N tracing model. Soil Biol. Biochem., 72: 44-54.

Noponen, M.R.A., Edwards-Jones, G., Haggar, J.P., Soto, G., Attarzadeh, N. and Healey, J.R. 2012. Greenhouse gas emissions in coffee grown with differing input levels under conventional and organic management. Agric. Ecosyst. Environ., 151: 6-15.

Padovan, M.P., Brook, R.M., Barrios, M., Cruz-Castillo, J.B., Vilchez-Mendoza, S.J., Costa, A.N. and Rapidel, B. 2018. Water loss by transpiration and soil evaporation in coffee shaded by Tabebuia rosea Bertol and Simarouba glauca dc. compared to unshaded coffee in sub-optimal environmental conditions. Agric. For. Meteorol., 248: 1-14.

Perfecto, I., Vandermeer, J., Mas, A. and Pinto, L.S. 2005. Biodiversity, yield, and shade coffee certification. Ecol. Econ., 54(4): 435-446.

Pilegaard, K. 2013. Processes regulating nitric oxide emissions from soils. Philosophical Trans. Royal Soc. B Biol. Sci., 368(1621): 20130126.

Rahman, N., Richards, K.G., Harty, M.A., Watson, C.J., Carolan, R., Krol, D., Lanigan, G.J. and Forrestal, P. J. 2021. Differing effects of increasing calcium ammonium nitrate, urea, and urea + NBPT fertilizer rates on nitrous oxide emission factors at six temperate grassland sites in Ireland. Agric. Ecosyst. Environ., 313: 107382.

Ravishankara, A.R., Daniel, J.S. and Portmann, R.W. 2009. Nitrous oxide (N_2O): The dominant ozone-depleting substance emitted in the 21st century. Science, 326(5949): 123-125.

Recio, J., Montoya, M., Ginés, C., Sanz-Cobena, A., Vallejo, A. and Alvarez, J.M. 2020. Joint mitigation of NH_3 and N_2O emissions by using two synthetic inhibitors in an irrigated cropping soil. Geoderma, 373: 114423.

Rivera Silva, M., del R., Nikolskii Gavrilov, I., Castillo Álvarez, M., Ordaz Chaparro, V.M., Díaz Padilla, G. and Guajardo Panes, R.A. 2013. Vulnerabilidad de la producción del café (*Coffea arabica* L.) al cambio climático global. Terra Latinoamer., 31(4): 305-313.

Rochette, P., Angers, D.A., Bélanger, G., Chantigny, M.H., Prévost, D. and Lévesque, G. 2004. Emissions of N_2O from Alfalfa and soybean crops in Eastern Canada. Soil Sci. Soc. Am. J., 68(2): 493-506.

Romero-Alvarado, Y., Soto-Pinto, L., García-Barrios, L. and Barrera-Gaytán, J.F. 2002. Coffee yields and soil nutrients under the shades of *Inga* sp. Vs. Multiple species in Chiapas, Mexico. Agrofor. Syst., 54(3): 215-224.

Sanz-Cobena, A., Lassaletta, L., Aguilera, E., Prado, A. del, Garnier, J., Billen, G., Iglesias, A., Sánchez, B., Guardia, G., Abalos, D., Plaza-Bonilla, D., Puigdueta-Bartolomé, I., Moral, R., Galán, E., Arriaga, H., Merino, P., Infante-Amate, J., Meijide, A., Pardo, G. and Smith, P. 2017. Strategies for greenhouse gas emissions mitigation in Mediterranean agriculture: A review. Agric. Ecosyst. Environ., 238: 5-24.

Sanz-Cobena, Alberto, Abalos, D., Meijide, A., Sanchez-Martin, L. and Vallejo, A. 2016. Soil moisture determines the effectiveness of two urease inhibitors to decrease N_2O emissions. Mitig. Adapt. Strateg. Glob. Chang., 21(7): 1131-1144.

Sarmiento-Soler, A., Vaast, P., Hoffmann, M.P., Rötter, R.P., Jassogne, L., van Asten, P.J.A. and Graefe, S. 2019. Water use of *Coffea arabica* in open versus shaded systems under smallholder's farm conditions in Eastern Uganda. Agric. For. Meteorol., 26: 231-242.

Šimek, M., JıČová, L. and Hopkins, D.W. 2002. What is the so-called optimum pH for denitrification in soil? Soil Biol. Biochem., 34(9): 1227-1234.

Ussiri, D. and Lal, R. 2012. Soil Emission of Nitrous Oxide and its Mitigation. Springer Science & Business Media.

Vaast, P., Bertrand, B., Perriot, J.J., Guyot, B. and Génard, M. 2006. Fruit thinning and shade improve bean characteristics and beverage quality of coffee (*Coffea arabica* L.) under optimal conditions. J. Sci. Food Agric., 86(2): 197-204.

Verchot, L.V., Hutabarat, L., Hairiah, K., Van Noordwijk, M. 2006. Nitrogen availability and soil N2O emissions following conversion of forests to coffee in southern Sumatra. Glob. Biogeochem. Cyc., 20(4).

Wang, H., Zheng, J., Fan, J., Zhang, F. and Huang, C. 2021. Grain yield and greenhouse gas emissions from maize and wheat fields under the plastic film and straw mulching: A meta-analysis. Field Crops Res., 270: 108210.