Vineyard Nitrous Oxide (N_2O) Emissions

Climate, irrigation, floor management interactions

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SOILS PROVIDE CRITICAL ECOSYSTEM functions, such as nutrient cycling, decomposition and water storage. They are a living ecosystem, and much of their functionality is controlled by the microbial communities present in them. During decomposition and cycling of carbon (C) and nitrogen (N), the microorganisms in soil naturally produce the greenhouse gases carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O). These three gases are the most abundant and critical greenhouse gases in our atmosphere. Increasing emissions from natural and abiotic sources contribute to global warming and climate change. How we manage our soils and nutrient inputs affects the quantity of these gases naturally produced in agricultural soils.

KEY POINTS

- Average annual N_2O emissions in vineyards are similar to those of other irrigated Mediterranean crops, approximately 1 pound N_2O-N per acre.
- The majority of vineyard N_2O emissions occur in the tractor rows, partly because this comprises the largest area of vineyards. High emissions in the tractor row occur following fall precipitation events or freeze/thaw events in the spring. High emissions in the vine row occur at fertilization and fall precipitation events.
- Nearly half of N_2O emissions occur during the non-growing season.
- To reduce emissions, when possible, offsetting soil and cover-cropping activities in the tractor row in relation to forecasted precipitation is recommended. Less floor management activity in the fall is also recommended.
- More data is needed on the variety and sequence of floor and tractor row management practices and their environmental outcomes.

What is Nitrous Oxide (N_2O)?

The concentration of all greenhouse gases in the atmosphere has steadily risen since pre-industrial times. While the majority of greenhouse gas emissions come from industrial or transportation sources, agriculture also plays a role, accounting for about 12 percent of CO_2-equivalent emissions per year.[1] Much of these emissions come from CO_2 and CH_4. Contributions from N_2O are estimated to be around 1 percent to 3 percent of total emissions or between 8 percent to 25 percent of agricultural emissions. This text focuses on emissions of N_2O. While N_2O is a smaller player than other greenhouse gases in terms of total emissions, emissions of N_2O have risen steadily in the last several decades. N_2O is a very powerful greenhouse gas, with a global warming potential nearly 300 times that of CO_2.

Unlike CO_2 and CH_4, the majority of N_2O emissions come from agricultural sources. Approximately 60 percent of global N_2O emissions have been attributed to agriculture.[2] Therefore, there is both pressure and interest within the agricultural sector to try to reduce N_2O emissions.

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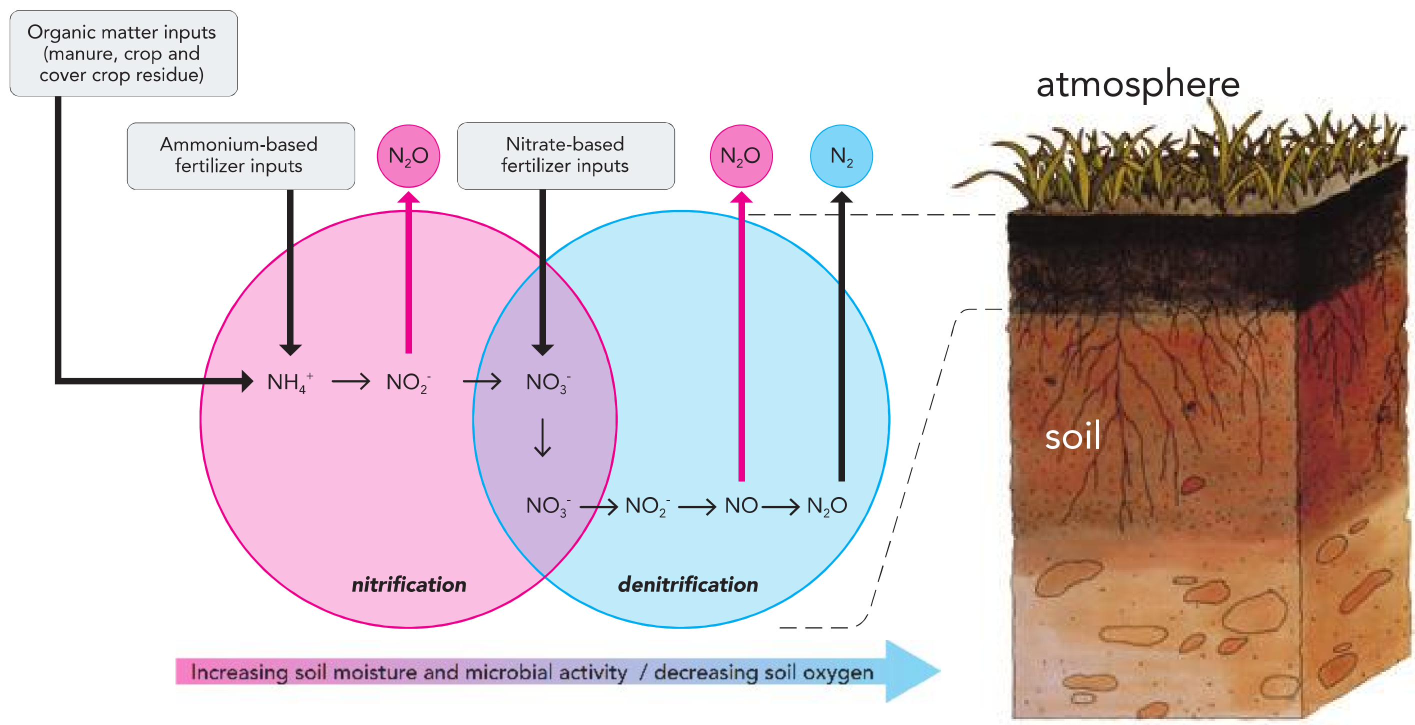
Sources of N_2O Emissions in Agricultural Systems

N_2O is primarily produced during microbial nitrogen cycling in the processes of nitrification or denitrification. (See **FIGURE 1**: Factors Influencing Cropland N_2O Emissions.) Nitrification is the conversion of ammonium (NH_4^+) to nitrate (NO_3^-), and it requires oxygen (O_2). During this process, N_2O is produced as a byproduct. Denitrification is the conversion of NO_3^- to N_2, where N_2O is produced as one of the intermediate steps. This process proceeds under low O_2 conditions.

Which process occurs, the process rates and the final products depend largely on O_2 concentrations. Oxygen concentrations in soil are inversely related to soil moisture, meaning that at high soil moisture, little soil O_2 exists and vice versa. Soil O_2 content declines when microbial activity is high because O_2 consumption increases.

Emissions of N_2O typically rise with increasing fertilizer nitrogen inputs, but it is really an alignment of soil environment (soil moisture, O_2 content and pH) and nutrient availability (nitrogen and carbon) that determines the magnitude of overall emissions. Farm management practices that

Factors influencing cropland N_2O emissions



N_2O emissions are determined by a combination of factors (below).
The impact of a change in one factor depends on the values of the other factors.

Direct controls on N_2O Production	Farm Management controls
Soil Moisture	Irrigation
Availability of NO_3^-, NH_4^-	Fertilizer input, Crop N uptake, residue input
Availability of soil carbon	Tillage, residue inputs
Microbial activity	Soil amendments (i.e., compost, manure)
Soil pH	Fertilizer input, soil amendment
Soil temperature	Residue cover

FIGURE 1. The pathways of the two main processes producing N_2O in the soil, nitrification and denitrification, and the major factors influencing these processes. N_2O emissions are determined by a combination of these factors. The impact of a change in one factor depends on the values of the other factors.

Adapted from Box 1 in Verhoeven et al, 2017. California Agriculture. 71(3):148-159, *https://doi.org/10.3733/ca.2017a0026*.

FIGURE 2. Depiction of the two vineyard zones defined and discussed in this article, the vine row and tractor row. Also shown are examples of gas flux chambers used to measure N_2O emissions at each location.

most affect N_2O emissions are the quantity and form of nitrogen fertilizer, irrigation quantity and method, the quality and amount of residue inputs, tillage intensity, soil amendments and residue cover. (See **FIGURE 1**: Factors Influencing Cropland N_2O Emissions.) In vineyard systems, where nitrogen inputs are low relative to other cropping systems, management factors aside from nitrogen input rates or type are likely to be of more importance in controlling N_2O emissions.

Many wine-growing regions are in relatively arid environments. In such environments, precipitation and irrigation have a strong influence on soil microbial processes, including N_2O emissions. In general, within agricultural systems and natural lands, high N_2O emissions occur when soils are quite moist—typically at a range of 70 percent to 90 percent water-filled pore space (WFPS)—but not saturated and have an excess of nitrate (NO_3^-), ammonium (NH_4^+) and easily digestible carbon. Note that when referring to the biological conditions within a soil, the term WFPS is often used to compare the soil moisture/oxygen status, as opposed to volumetric water content, because WFPS accounts for differences in soil texture and compaction.

Soil management and inputs typically occur in two distinct zones in a vineyard, the vine row and tractor row. (See **FIGURE 2**: Two Vineyard Zones: Vine Row and Tractor Row.) Nitrogen inputs into the vine row are typically delivered as "fertigation" through permanently installed irrigation systems (buried or surface drip or microjet sprinklers). Additionally, the vine rows may or may not receive organic amendments coming from compost, winery waste residues, grape-thinning or pruning residues. In the vine rows these amendments are not incorporated into the soil, but remain on the surface.

Nitrogen inputs into the tractor row come solely from organic amendments such as those listed above, plus from cover crops. Cover crops are typically planted as a legume mix, legume-cereal mix, cereal or simply let to seed with native vegetation.

Vineyards may seed a cover crop in alternate years in alternate tractor rows, so for any single tractor row it is seeded with a cover crop just once every two years, or a cover crop may be seeded each year. Cover crops are often seeded in the fall following harvest and mowed in the spring/summer; they may be plowed shortly after mowing in the spring or in the fall following harvest.

early cover crop growth | peak growth | after mowing

FIGURE 3. Gas flux chambers placed in a tractor row of a vineyard in Northern California. From left to right, the progression of cover crop growth is shown. The large differences in vegetation over time and between the vine and tractor rows, demonstrates the need for gas and nutrient measurements across locations and throughout the year. California Agriculture 71(3):148-159. © 2017 The Regents of the University of California.

FIGURE 4. Examples of different cover crop management practices. On the left is a seeded legume-grain mixture at peak growth in the spring. In the middle is a tilled tractor row adjacent to a native grass tractor row in the late spring. On the right is native vegetation-legume cover crop in the fall. These examples demonstrate how different cover crop practices can supply quite different amounts of organic matter, nitrogen and carbon and at different periods of the year.

Alternatively, vineyards may opt for no-tillage with the cover crop largely drying up in the summer or termination of the cover crop by grazing. In sum, the industry is dynamic and diverse in the management of tractor row cropping. Naturally, this large variety of practices results in variable amounts and timing of organic matter and nutrient inputs to vineyard soils. (See FIGURE 3: Gas Flux Chambers in a Tractor Row at Multiple Cover Crop Growth Stages, and FIGURE 4: Different Cover Crop Management Practices.)

Compared to other cropping systems, the number of studies investigating seasonal or annual N_2O emissions in vineyards is relatively few and does not comprehensively cover the variety of management practices employed. To our knowledge, the data available has exclusively been collected in Northern or Central California, aside from one study conducted in the Okanagan Valley, British Columbia, Canada. The practices investigated in the studies include comparisons of tillage regime,[3,4] cover cropping and mixtures,[5] irrigation methods,[6,4] organic amendments[6,4] and baseline measurements.[7,8]

N_2O Emissions in Vineyards

Among the four studies that reported annual N_2O emissions (22 observations in total), average emissions across all management practices were 1.09 ± 0.77 pounds N_2O-N per acre. These annual emissions are similar to those observed in many irrigated and perennial Mediterranean cropping systems [9,10] and are lower than many field crop systems.

For example, emissions reaching 6.3 to 8.9 pounds N_2O-N per acre have been observed in Midwestern corn systems.[11] However, the total N fertilizer application in vineyards is generally quite low compared to other cropping systems, and actually relative to the amount of nitrogen applied (also called an emission factor), emissions in vineyards are somewhat higher than found in other crops.[10,12] The average emission factor of the four studies was 3.7 percent $\pm$ 2.1 percent; in comparison, the average for perennial Mediterranean cropping systems is 1 to 2 percent. The emission factor in vineyards can be quite variable from year to year. This variability arises largely from biennial

cover crop inputs and the difficulty of predicting nitrogen and carbon release from organic matter in tractor rows.

Across all the studies, emissions of N_2O in the fallow or non-growing season accounted for almost half of annual emissions (44 ± 18 percent). (See **FIGURE 5**: Percent of Annual Emissions.) Relative to other cropping systems, higher variability between years and in the seasonal contribution to annual emissions is found in vineyard systems. This variability likely arises from a combination of biennial cover crop management practices and variable climatic effects.

Relative to other cropping systems, fertilizer nitrogen rates among the studies were low but variable between years, often varying by a factor of two between years. Undoubtedly, this also contributes to greater inter-annual variability. Because of longer-term management practices, we recommend that emissions and emission factors in vineyard systems take into account a full, multi-year management cycle. For example, emissions may be best calculated over two years relative to two years of nitrogen inputs.

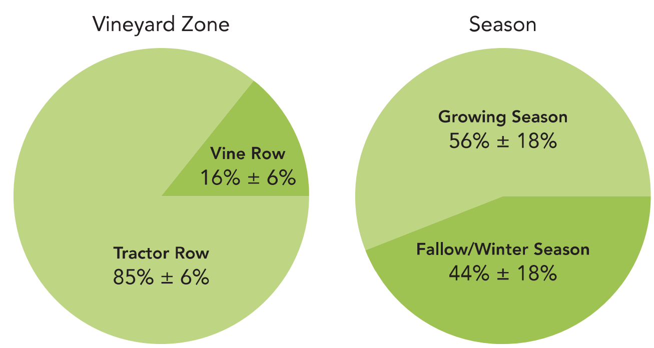


FIGURE 5. Percent of annual emissions occurring from a given vineyard zone or season. Vineyard zone data was only available for two studies, each lasting two years (n=4) (Garland et al., 2014; Verhoeven and Six, 2014). Seasonal data was available from an additional study by (Fentabil et al., 2016) (n=16).

Adapted from Figures 1 and 2 in Verhoeven et al, 2017. California Agriculture. 71(3):148-159, https://doi.org/10.3733/ca.2017a0026.

Cover Crop Management

Among the studies that reported annual emissions for both vine rows and tractor rows, the tractor rows comprised, on average, 85 percent of annual emissions. The large influence of the tractor rows reflects, in part, the larger surface area they cover, usually accounting for 70 percent to 80 percent of the vineyard floor. Therefore, to effectively reduce N_2O emissions, management of the tractor rows is necessary.

Cover cropping tends to increase emissions of N_2O relative to bare, tilled soil.[5,7] However, the many benefits of cover cropping, such as erosion control, nutrient and water storage and provision, improved soil structure, increased organic matter and carbon storage, likely outweigh any increase in N_2O emissions.

Currently, no data is available that compares cereal and legume-based cover crops. Legume cover crops can potentially result in higher N_2O emissions because of their higher plant nitrogen content, which can result in higher soil N once the cover crop is incorporated into the soil. It is possible that cover cropping with a cereal (such as rye, triticale or native grasses) will provide many of the benefits listed above but with reduced N_2O emissions relative to a legume-based cover crop. This is an area where more research is needed.

Beyond the choice of which cover crop species to plant, management activities, such as mowing, grazing or tillage, can affect N_2O emissions. Mowing or incorporation of a cover crop may occur in the spring or fall. From the data available, there does not seem to be a uniform effect of mowing versus incorporation on N_2O emissions. This is because, in either management practice, the availability of nutrients coming from the cover crop, and ultimately N_2O emissions, depends on moisture and temperature, which vary by site and year.

To the best of our knowledge, no data is currently available on the effect of grazing in vineyard cover crops on N_2O emissions. In one study, spring mowing caused no effect on emissions[8] while in another study a peak in emissions was observed following spring mowing.[3] Spring incorporation of a cover crop may also cause small emission peaks.[3,4]

Similar to emission peaks following rain or fertilization events, emissions associated with mowing or incorporation were short-lived, lasting less than one week. These emissions are, in general, of equal or lower magnitude than emissions coming from fertigation events.[3,8]

There is some evidence that incorporation in the fall may enhance N_2O emissions relative to spring tillage or mowing.[5] This may be due to an effect of higher soil moisture in the fall or relate to an increase in nutrient availability. A number of studies have shown that NO_3^- and NH_4^+ concentrations typically increase over the course of the summer. Again, timing of mowing or incorporation of cover crops is another area of management that needs more research.

Fertilization and Irrigation Management

Fertilization or irrigation management practices almost exclusively affect N_2O emissions coming from the vine row. Typically, these emission peaks last only a few days and return to baseline levels within one week. Among the data available, the magnitude of these peaks varied from 0.003 pounds per acre per day to more than 0.04 pounds per acre per day.[4,8]

Studies with higher N application rates tend to have higher N_2O emissions. However, within one study, the quantity of fertilizer applied at an individual event did not necessarily relate to N_2O emissions. For example, a fertilizer application of 5 pounds N per acre may induce equally or higher emissions as an application of 10 pounds N per acre. This variation is due to interactions with soil temperature, moisture, available carbon and plant nitrogen uptake. If plant growth is vigorous, nitrogen will be taken up more quickly, with less available for nitrogen transformations and N_2O emissions.

Organic materials can be applied to the vine row. One study investigated the use of compost or urea and bark mulch application to vine rows.[6] Bark mulch reduced emissions by 28 percent while compost reduced emissions by 18 percent relative to urea, but this result was not statistically significant.

The choice of irrigation system can reduce emissions. One study showed that irrigation by microjet sprinklers reduced N_2O emissions by 29 percent relative to drip irrigation.[6] A similar result was found in irrigated almond production;[13] these results are likely the result of a more even and broader moisture application.

Management Practices to Reduce N_2O Emissions

Increase nitrogen use efficiency: To the degree possible, time nitrogen application with plant demand. If using cover crops to supply N, mowing in the midspring or early summer may deliver the most N to growing vines. Avoid fall N application or cover crop mowing if possible. Increased precipitation in the fall can lead to greater N_2O emissions and nitrate leaching, both reducing N use efficiency.

Increase water-use efficiency: Buried drip and microjet irrigation systems can increase water-use efficiency and reduce N_2O emissions.

Source of nitrogen does not matter: Synthetic N and organic amendments both contribute to N_2O emissions. Predicting the timing of N availability supplied from organic sources is difficult because it relates to soil moisture, temperature and land-use history. Organic N sources can increase both the quantity and variability in N_2O emissions by increasing the likelihood of climate-microbe interactions. However, organic matter N sources, such as cover crops or manure, provide valuable carbon and nutrients to the soil that, in the long term, will help achieve more efficient N and water use. A holistic and long-term approach to management is needed.

Importance of multiple variables in N_2O emissions: Among the studies reviewed here, total N fertilization rates (cover crop + synthetic N) only partially explained N_2O emissions. Other factors, such as irrigation method, soil type, climate (British Columbia and California) and year-to-year climate variation, also had a strong impact.

This information was adapted from Verhoeven et al., California Agriculture, July-September 2017. Vol 71, 148-159.

Precipitation and Thaw Events are Strong Drivers of N_2O Emissions

Among the studies in California, high emissions were associated with precipitation events, in particular, the first rain event of the fall/winter season in all studies. Large pulses of emissions were observed in both the vine row and tractor row.

In the tractor row, precipitation events were by far the largest driver of emissions, much greater than cover crop management activities (tillage and mowing). These emission peaks can be of similar or greater magnitude as fertigation or rain-induced emissions in the vine row.

In one study, the spike in tractor row emissions at the onset of rains was 10 times higher than in the vine row at the same time. However, such a dramatic difference between the vine row and tractor row was not always observed. The effect of precipitation on the tractor row is the result of an interaction between the availability of soil inorganic nitrogen from a cover crop and soil moisture. High emission peaks have also been observed in vine rows at the time of the first fall rains.[6,7,8,14]

In both vineyard positions, subsequent rain events caused much smaller or negligible increases in emissions. The spike observed with the first rains appears to mostly relate to increases in NH_4^+ availability over the summer and may relate to increased availability of carbon and nitrogen following harvest.

In machine-harvest systems, a significant amount of grape and leaf residue is crushed and dropped on the vineyard floor, and the residue may fuel N_2O emissions. In the tractor row, nutrient inputs from mowed cover crop residues, active root inputs or the whole biomass, if incorporated, all cause an increase in N_2O when soil moisture rises. In a study in the Okanagan Valley, high emissions were not the result of fall rains but of soil thawing in the spring.[6] Emissions in the pre-growing season thaw period accounted for 37 percent and 61 percent of emissions in two consecutive years, respectively.

What Can You Do in Your Vineyard to Help Reduce N_2O Emissions?

Practices that improve the efficiency of nitrogen use and water use are likely to be the most effective to reduce N_2O emissions. Use of microjet sprinklers and split applications of N fertilizer are recommended.

If possible, avoiding N application or cover crop management events (tillage or mowing) is recommended when rain is predicted in the near future. Factoring rain forecasts into management timing decisions adds another layer to a potentially complex decision-making process and may not always be possible. For Mediterranean climate systems, this could be achieved by performing less, or avoiding entirely, soil, cover crop and N management practices in the fall. However, a shift in practices must not compromise long-term vine health and grape quality.

Overall, the data available is almost exclusively from Northern California, and comprehensive data for a variety of management practices and sequences of practices is not available. The wine industry is dynamic and open to sustainable soil-management strategies, many of which involve permutations of tractor row cover-cropping and organic amendments. Many of these practices are in place because it is known that they can help bring and retain more carbon in the soil, increase soil fertility and water retention, and prevent erosion. We want to continue to encourage the use of such practices because they address long-term soil and environmental health.

Vineyard managers need more information to holistically evaluate the environmental impacts of varied practices used in vineyards. Among ongoing research initiatives is a collaborative project between **California Polytechnic State University, San Luis Obispo** and two vineyards in the California Central Coast that will determine N_2O emissions following compost application, in combination with tillage or grazing of the cover crops. This project will also include a survey to elucidate the practices being currently used by the growers in the region and observed benefits for soil health and fruit quality. We look forward to collecting and sharing new environmental data on vineyard soil management practices. **WBM**