



Three Webinars on Nitrogen Management and Nitrous Oxide Emissions in Pacific Northwest Agriculture:

Nitrogen Cycling and Losses in Agricultural Systems

Webinar presentation by Kristy Borrelli, Extension Specialist, Regional Approaches to Climate Change (REACCH), University of Idaho. March 13, 2014.

Nitrous Oxide Emissions in Inland Pacific Northwest Cropping Systems

Webinar presentation by Georgine Yorgey, Associate in Research, WSU Center for Sustaining Agriculture and Natural Resources. April 17, 2014.

Nitrogen Management and Climate Change Mitigation in Pacific Northwest Cropping Systems

Webinar presentation by Georgine Yorgey, Associate in Research, WSU Center for Sustaining Agriculture and Natural Resources. April 17, 2014.

Further Reading

Adewale, C., B. Carlson, L. Carpenter-Boggs, D. Granatstein, M. Heppenstall, S. Higgins, R. Nelson, C. Stockle, A. Thatcher, S. Verhey, B. Weddell and U. Zaher. 2013. What if? Options for a winter squash, potato, cauliflower rotation. Poster presented at: Washington State Tilt Producers Conference, Yakima, WA. November 8-10, 2013.

Poster presentation of the alternative nitrogen (N) management scenarios developed as part of the OFoot project (<http://csanr.wsu.edu/organic-farming-footprints/>).

Akiyama, H., X. Yan and K. Yagi. 2009. Evaluation of effectiveness of enhanced-efficiency fertilizers as mitigation options for N₂O and NO emissions from agricultural soils: Meta-analysis. *Global Change Biology*. 16:1837–1846.

Global meta-analysis of the effectiveness of enhanced efficiency fertilizers in reducing nitrous oxide (N₂O) and nitric oxide (NO) emissions.

Bateman, E.J. and E.M. Baggs. 2005. Contributions of nitrification and denitrification to N₂O emissions from soils at different water-filled pore space. *Biology and Fertility of Soils*. 41:379–388.

Laboratory study investigating the contributions of multiple microbial pathways to N₂O production under various amounts of water filled pore space.

Bellingham, B.K. 2009. Method for irrigation scheduling based on soil moisture data acquisition. [Online]. Available at: <http://www.stevenswater.com/articles/irrigationscheduling.aspx>. (verified 18 April 2014).

This document is the source of the graphic on water pore space that was included (with permission) in the third webinar.

Bouwman, A.F., L.J.M. Boumans and N.H. Batjes. 2002a. Emissions of N₂O and NO from fertilized fields: Summary of available measurement data. *Global Biogeochemical Cycles*. 16:1058.

Summary of the datasets on which their 2002 analysis of the factors correlated with N₂O emissions was based (this analysis was updated in 2006- see Stehfest and Bouwman, 2006). The Intergovernmental Panel on Climate Change (IPCC) Tier 1 approach (2006) is based on this dataset, along with others.

Bouwman, A.F., L.J.M. Boumans and N.H. Batjes. 2002b. Modeling global annual N₂O and NO emissions from fertilized fields. *Global Biogeochemical Cycles*. 16:1080.

A meta-analysis of data on N₂O emissions in agricultural soils, including 846 measurements from 126 different studies. The IPCC Tier 1 approach (2006) is based on this dataset, along with others. This analysis was updated by Stehfest and Bouwman (2006).

Brown, T., C. Lee, C. Kruger, and D. Huggins. 2014. Nitrous oxide emissions protocols for the Pacific Northwest. p. 48–49. *In: Regional Approaches to Climate Change for Pacific Northwest agriculture*. February 15, 2013-February 15, 2014. University of Idaho, Moscow, ID. [Online]. Available at: <https://www.reacchpna.org/files/2613/9336/7697/REACCHReportyear3.pdf>. (verified 17 April 2014).

A short article, written for a non-scientific audience, summarizing the "road test" of nitrous oxide emissions reduction protocols in the Pacific Northwest (PNW) that was mentioned at the end of the third webinar.

Burton, D.L., X. Li, and C.A. Grant. 2008. Influence of fertilizer nitrogen source and management practice on nitrous oxide emissions from two Black Chernozemic soils. *Canadian Journal of Soil Science*. 88:219-227.

A field study of the influence of N source, time of application, and method of application on N₂O emissions on no till or reduced tillage wheat in Manitoba.

Cameron, K.C., H.J. Di and J.L. Moir. 2013. Nitrogen losses from the soil/plant system: A review. *Annals of Applied Biology*. 162:145-173.

A current review paper that describes the N cycle in temperate soil/plant systems, processes involved in each individual N loss pathways, factors affecting the amounts of losses and methods available to reduce losses. Each section is broken up into **Impacts** of the specific loss; **Processes** (N cycle) that result in the loss; **Factors** that affect losses and **Methods** to reduce losses.

Cassman, K.G., A. Dobermann and D.T. Walters. 2002 Agroecosystems, nitrogen-use efficiency, and nitrogen management. *Ambio*. 31:132-140.

Overview of nitrogen use efficiency (NUE) - a bit complex, but provides good breakdown. Includes baselines for cereal use efficiencies and estimates of residual N for corn and rice. Discussion of some simple management factors and climate/weather conditions which can affect NUE. Also includes a good overview on practical methods and limitations for improving NUE from profit, management and policy - suggests research focus areas.

Cavigelli, M.A., S.J. Del Grosso, M.A. Liebig, C.S. Snyder, P.E. Fixen, R.T. Venterea, A.B.

Leytem, J.E. McLain and D.B. Watts. 2012. US agricultural nitrous oxide emissions: Context, status, and trends. *Frontiers in Ecology and the Environment*. 10:537-546.

Importance of N₂O in the environment and causes of its increase from US agricultural production. Includes current values of emissions and N use from IPCC, EPA and USDA ERS and NASS etc. in discussions of current trends. Discusses importance of N balance or partial N balance in effectively estimating NUE and how these estimates fall short.

Chadwick, D., S. Sommer, R. Thorman, D. Fanguero, L. Cardenas, B. Amon and T. Misselbrook. 2011. Manure management: Implications for greenhouse gas emissions. *Animal Feed Science and Technology*. 166-167:514–531.

For those interested in the N₂O emissions associated with the land application of manures, a review article that can serve as a reasonable starting point.

Cochran, V.L., L.F. Elliott and R.I. Papendick. 1981. Nitrous oxide emissions from a fallow field fertilized with anhydrous ammonia. *Soil Science Society of America Journal*. 45:307-310.

A field study of N₂O emissions from a fallow Palouse silt loam for 41 days following N application at a variety of rates.

Collins, H.P., A.K. Alva, J.D. Streubel, S.F. Fransen, C. Frear, S. Chen, C. Kruger and D. Granatstein. 2011. Greenhouse gas emissions from an irrigated silt loam soil amended with anaerobically digested dairy manure. *Soil Science Society of America Journal*. 75:2206.

Field study of greenhouse gas (GHG) emissions from land application of AD dairy manure in Washington State.

Collins, H.P., S. Haile-Mariam and S.S. Higgins. 2010. Greenhouse gas fluxes from irrigated sweet corn (*Zea mays* L.) and potato (*Solanum tuberosum* L.). *In: Climate friendly farming: Improving the carbon footprint of agriculture in the Pacific Northwest*. CSANR Research Report 2010-001. Center for Sustaining Agriculture and Natural Resources, Washington State University, Wenatchee, WA.

Field study of GHG fluxes from conventionally tilled and reduced tillage sweet corn-sweet corn-potato rotation in the irrigated region of Washington. See also Haile-Miriam, 2008.

Dawson, J.C., D.R. Huggins, S.S. Jones, and K. Murphy. 2011. Evaluation of winter wheat breeding lines for traits related to nitrogen use under organic management. *Organic Agriculture*. 1:65–80.

An article discussing the traits important for N use under low N conditions, including organic management.

Desjardins, R.L., E. Pattey, W.N. Smith, D. Worth, B. Grant, R. Srinivasan, J.I. MacPherson and M. Mauder. 2010. Multiscale estimates of N₂O emissions from agricultural lands. *Agricultural and Forest Meteorology*. 150:817–824.

Compares estimates of N₂O emissions from three different methods: flux towers (eddy covariance), aircraft (relaxed eddy covariance) and modeled (DNDC).

Dusenbury, M.P., R.E. Engel, P.R. Miller, R.L. Lemke and R. Wallander. 2008. Nitrous oxide emissions from a Northern Great Plains soil as influenced by nitrogen management and cropping systems. *Journal of Environment Quality*. 37:542.

A two year field study of N₂O emissions under varying levels of N application and in various wheat-based cropping systems.

Eagle, A.J., L.P. Olander, L.R. Henry, K. Haugen-Kozyra, N. Millar and G.P. Robertson. 2012. Greenhouse gas mitigation potential of agricultural land management in the United States: A synthesis of the literature, third edition. Nicholas Institute for Environmental Policy Solutions, Duke University, Durham, NC.

A thorough review of the quantitative GHG mitigation potential of various land management strategies in the U.S., including changes in N fertilizer management, and impacts on N₂O from changes in irrigation management and tillage.

Ehmke, T. 4R nutrient management: Right source. Right rate. Right time. Right place. Right now. 2012. *Crops and Soils Magazine*. American Society of Agronomy*. [Online]. Available at: <https://www.agronomy.org/files/publications/crops-and-soils/4r-nutrient-management.pdf>. (verified, 17 April 2014).

* Note: 4R Plant Nutrition: A Manual for improving the management of plant nutrition issued by the International Plant Nutrition Institute (IPNI) available for purchase at: <http://www.ipni.net/ipniweb/portal.nsf/0/231EA9CAE05F5D24852579B200725EA2> (verified, 17 April 2014).

4R nutrient management is a proposed strategy for reducing N losses from fertilization in plant/soil systems, focusing on right rate, right source, right time, right place.

Engel, R., D.L. Liang, R. Wallander and A. Bembenek. 2010. Influence of urea fertilizer placement on nitrous oxide production from a silt loam soil. *Journal of Environmental Quality*. 39:115-125.

This field study, from no-till canola grow in a silt loam soil near Bozeman, MT, indicates that there may be lower N₂O emissions from broadcast urea, intermediate emissions from banded, and highest emissions from nested placement.

Esser, A. 2014. Nitrogen fertilizer decision support tool. Small Grains Extension Web Site, Washington State University Extension. [Online]. Available at: <http://www.smallgrain.wsu.edu>.(verified 18 February 2014).

The web-based N fertilizer calculator for winter wheat referred to (and partially shown) in the third webinar.

Fiez, T., B. Miller, and W. Pan. 1994. Assessment of spatially variable nitrogen fertilizer management in winter wheat. *Journal of Production Agriculture*. 7:86–93.

An older study from the PNW of variable N applications. In this study, N rates on soft white winter wheat were reduced roughly 30-45% under precision N application compared to uniform application.

Grant, R.F., E. Pattey, T.W. Goddard, L.M. Kryzanowski and H. Puurveen. 2006. Modeling the effects of fertilizer application rate on nitrous oxide emissions. *Soil Science Society of America Journal*. 70:235.

A modeling study indicating that the effects of past and current fertilizer use are both important to emissions factors- and emissions factors should rise with the extent to which applications exceed ecosystem N uptake capacity (crop + soil) over time.

Gregorich, E., P. Rochette, A. Vandenbygaart and D. Angers. 2005. Greenhouse gas contributions of agricultural soils and potential mitigation practices in Eastern Canada. *Soil and Tillage Research*. 83:53-72.

This article, covering the breadth of information available on GHG emissions in eastern Canada, includes information on sizeable N₂O fluxes during winter/spring freeze-thaw cycles.

Van Groenigen, J.W., G.L. Velthof, O. Oenema, K.J. Van Groenigen and C. Van Kessel. 2010. Towards an agronomic assessment of N₂O emissions: A case study for arable crops. *European Journal of Soil Science*. 61:903-913.

Expressing N₂O emissions in relation to crop productivity, the authors find minimal yield-scaled N₂O emissions at intermediate fertilizer rates. They also find a negative relationship between N use efficiency and yield-scaled N₂O emissions.

Haile-Mariam, S., H.P. Collins and S.S. Higgins. 2008. Greenhouse gas fluxes from an irrigated sweet corn-potato rotation. *Journal of Environmental Quality*. 37:759-771.

The published journal article that is a companion to the Collins et al. (2010) paper that measured N₂O fluxes in a sweet corn-sweet corn -potato rotation in central Washington.

Halvorson, A.D. 2010. The effect of enhanced-efficiency fertilizers on nitrous oxide emissions from various cropping systems. [Online]. Available at: <http://www.fertilizer.org/layout/set/print/HomePage/LIBRARY/Conference-papers/Agriculture-Conferences/2010-IFA-New-Ag-International-Event> (verified 23 May 2013). Presented at: International Conference on Enhanced-Efficiency Fertilizers, Miami, FL. March 23-24, 2010.

A presentation summarizing the coordinated USDA-ARS study examining the effects of enhanced-efficiency fertilizers and other fertilizer types across various cropping systems, climates, and soils. This presentation includes the results of J. Smith's study in Pullman, which was included in the second and third webinars.

Halvorson, A.D., K.L. Steenwerth, E.C. Suddick, M.A. Liebig, J.L. Smith, K.F. Bronson and H.P. Collins. 2012. Management to reduce greenhouse gas emissions in western U.S. croplands. In: *Managing agricultural greenhouse gases*. M.A. Liebig, A.J. Franzluebbers, and R.F. Follett (eds.). Academic Press. pps. 167-182.

The most recent regionally focused (western U.S.) review of N₂O emissions (among other GHGs).

Hao, X., C. Chang, J.M. Carefoot, H.H. Janzen, and B.H. Ellert. 2001. Nitrous oxide emissions from an irrigated soil as affected by fertilizer and straw management. *Nutrient Cycling in Agroecosystems*. 60:1-8.

Field study of the impacts of timing of N fertilizer application and straw/tillage practices on N₂O emissions from wheat and canola in Lethbridge, Alberta.

Henault, C., A. Grossel, B. Mary, M. Roussel and J. Léonard. 2012. Nitrous oxide emission by agricultural soils: A review of spatial and temporal variability for mitigation. *Pedosphere*. 22:426-433.

A review article of the literature about spatial and temporal variability of N₂O emissions.

Hoben, J.P., R.J. Gehl, N. Millar, P.R. Grace and G.P. Robertson. 2011. Nonlinear nitrous oxide (N₂O) response to nitrogen fertilizer in on-farm corn crops of the U.S. Midwest. *Global Change Biology*. 17:1140–1152.

A field study of N₂O emissions at various rates on Kellogg Biological Station and commercial farm settings. Found exponential relationship between N application rates and N₂O emissions.

Huggins, D., J. Wavrin, D. Brown, A. Esser, and K. Painter. 2014. Precision nitrogen management: Developing science-based practices. p. 22–23. *In: Regional Approaches to Climate Change for Pacific Northwest agriculture*. February 15, 2013-February 15, 2014. University of Idaho, Moscow, ID. [Online]. Available at: <https://www.reacchpna.org/files/2613/9336/7697/REACCHReportyear3.pdf>. (verified 17 April 2014).

A short article, written for a non-scientific audience, summarizing recent precision N research in dryland systems in the PNW.

Hultgreen, G.A. and P. Leduc. 2003. Effect of fertilizer placement, formulation, timing and rate on greenhouse gas emissions and agronomic performance. Agriculture and Agri-Food Canada and Prairie Agricultural Machinery Institute, Swift Current, SK.

A study showing impact on N₂O emissions from a variety of fertilizer-related factors on canola, flax, and wheat in western Canada (Saskatchewan). Factors considered included N placement (side-banded, mid-row banded, broadcast), N fertilizer formulation (urea, anhydrous ammonia), application timing (fall, spring), N rate, and phosphorus (P) placement (side-banded, with the seed).

Idaho DEQ. 2008. Idaho greenhouse gas inventory and reference case projections, 1990-2020. Idaho Department of Environmental Quality and Center for Climate Strategies, Boise, ID.

Idaho's most recent GHG inventory, completed in 2008, and covering 1990-2005 (with projections to 2020). Includes estimates of N₂O production from agricultural soils.

Izaurrealde, R.C., R.L. Lemke, T.W. Goddard, B. McConkey and Z. Zhang. 2004. Nitrous oxide emissions from agricultural toposequences in Alberta and Saskatchewan. *Soil Science Society of America Journal*. 68:1285-1294.

Measurements of N₂O emissions by landscape position (two sites) are used to calculate field level N₂O emissions. They find that landscape position is significantly correlated with N₂O emissions, but that the patterns vary seasonally.

Jones, C., B.D. Brown, R. Engel, D. Horneck and K. Olson-Rutz. 2013. Factors affecting nitrogen fertilizer volatilization. Montana State University Extension. EB0208. pps. 1-6. [Online]. Available at: <http://landresources.montana.edu/soilfertility/PDF/pub/UvolfactEB0208.pdf>. (verified 17 April 2014).

Jones, C., B.D. Brown, R. Engel, D. Horneck and K. Olson-Rutz. 2013. Management to minimize nitrogen fertilizer volatilization. Montana State University Extension. EB0209. pps. 1-5. [Online]. Available at:

<http://msuextension.org/publications/AgandNaturalResources/EB0209.pdf>. (verified 17 April 2014).

A pair of Extension bulletins that address both the causes of volatilization of N fertilizers and the management options for controlling these losses from croplands in the Northwestern US.

Kaiser, E.A. and R. Ruser. 2000. Nitrous oxide emissions from arable soils in Germany: An evaluation of six long-term field experiments. *Journal of Plant Nutrition and Soil Science*. 163:249-259.

An older field study of N₂O emissions. At two sites, the N in/out balance (capturing the efficiency of N fertilization for crop production and allowing for N mineralization from the soil) was a suitable predictor of N₂O emissions.

De Klein, C., R.S.A. Novoa, S. Ogle, K.A. Smith, P. Rochette, T.C. Wirth, B.G. McConkey, A. Mosier and K. Rypdal. 2006. N₂O Emissions from managed soils, and CO₂ emissions from lime and urea application. *In: Eggleston, S., Buendia, L., Miwa, K., Ngara, T., Tanabe, K. (eds.), 2006 IPCC guidelines for national greenhouse gas inventories*. Institute for Global Environmental Strategies, Hayama, Kanagawa, Japan.

This document, produced by the IPCC, provides guidance for calculating N₂O emissions from agricultural soils.

Koenig, R.T. 2005. Dryland winter wheat Eastern Washington nutrient management guide. Washington State University Extension. EB1987. pps. 1-4. [Online]. Available at: <http://cru.cahe.wsu.edu/CEPublications/EB1987E/EB1987E.pdf>. (verified 17 April 2014).

A nutrient management guide for N and P fertilization in winter wheat production, specifically in the dryland region of Eastern Washington State. Includes worksheet for calculating rates.

Kostyanovsky, K., D. Huggins, C. Stockle, J.L. Smith, J. Morrow, B. Lamb, S. Pressley, S. Waldo, D. Brown, and B. Pan. 2014. N₂O and CO₂ production in wheat-based cropping systems. p. 42–43. *In: Regional Approaches to Climate Change for Pacific Northwest agriculture*. February 15, 2013-February 15, 2014. University of Idaho, Moscow, ID. [Online]. Available at: <https://www.reacchpna.org/files/2613/9336/7697/REACCHReportyear3.pdf>. (verified 17 April 2014).

A short summary, aimed at a non-scientific audience, of the ongoing work under the REACCH-PNA project to monitor N₂O fluxes from agricultural systems in the inland PNW, with and without added water and N.

Liebig, M.A., J.A. Morgan, J.D. Reeder, B.H. Ellert, H.T. Gollany and G.E. Schuman. 2005. Greenhouse gas contributions and mitigation potential of agricultural practices in Northwestern USA and Western Canada. *Soil and Tillage Research*. 83:25–52.

A review article of GHG emissions from cropland and rangeland soils for the northwestern US and western Canada, including much of the PNW, though excluding the Columbia Basin.

Mathieu, O., J. Leveque, C. Henault, M. Milloux, F. Bizouard and F. Andreux. 2006. Emissions and spatial variability of N₂O, N₂, and nitrous oxide mole fraction at the field scale, revealed with ¹⁵N isotopic techniques. *Soil Biology and Biochemistry*. 38:941–951.

A database of the N₂O mole fraction measured at the field scale, and a test of several hypotheses concerning its regulation.

McSwiney, C.P. and G.P. Robertson. 2005. Nonlinear response of N₂O flux to incremental fertilizer addition in a continuous maize (*Zea mays* L.) cropping system. *Global Change Biology*. 11:1712–1719.

A field study indicating that the relationship between N₂O fluxes and N availability is non-linear.

Millar, N., G.P. Robertson, P.R. Grace, R.J. Gehl and J.P. Hoben. 2010. Nitrogen fertilizer management for nitrous oxide mitigation in intensive corn (Maize) production: An emissions reduction protocol for U.S. Midwest agriculture. *Mitigation and Adaptation Strategies for Global Change*. 15:185–204.

Discusses fertilizer management for N₂O mitigation in intensive corn production, focusing on the Midwestern US. Includes an estimate that fertilizer application could be reduced by 12-15%.

Nitrogen Notes is a series of bulletins written by scientific staff of the International Plant Nutrition Institute (IPNI). Topics include: Managing Nitrogen, Managing Urea, Nitrate Leaching and Nitrification. [Online]. Available at: <http://www.ipni.net/NitrogenNotes>. (verified 17 April 2014).

Oregon Global Warming Commission. 2011. Oregon Global Warming Commission report to the Legislature 2011, including key actions and results from the Commission's interim roadmap to 2020. Oregon Department of Energy, Salem, OR.

Appendix 2 of this report includes an inventory of Oregon's GHG emissions from 1990-2008, with an estimate of N₂O emissions from agricultural soils. The most recent emissions inventory for Oregon is available at http://www.oregon.gov/deq/AQ/Documents/OregonGHGinventory07_17_13FINAL.pdf, but the older inventory was used to allow for comparison with Idaho data.

Parkin, T.B. 2008. Effect of sampling frequency on estimates of cumulative nitrous oxide emissions. *Journal of Environment Quality*. 37(4):1390.

An exploration of the impact of measurement interval on estimates of N₂O emissions.

Phillips, R.L., D.L. Tanaka, D.W. Archer and J.D. Hanson. 2009. Fertilizer application timing influences greenhouse gas fluxes over a growing season. *Journal of Environmental Quality*. 38:1569-1579.

Investigation of the impact of timing of corn fertilization in GHG fluxes in the Great Plains.

Ravishankara, A.R., J.S. Daniel and R.W. Portmann. 2009. Nitrous oxide (N₂O): The dominant ozone-depleting substance emitted in the 21st Century. *Science*. 326:123-125.

Analysis carried out by the authors indicates that N₂O is the single most important ozone-depleting substance, and expected to remain the largest throughout the 21st century.

Roberts, T. 2006. Improving nutrient use efficiency. *In*: Proceedings of the IFA agriculture conference "Optimizing resource use efficiency for sustainable intensification of agriculture, Kunming, China. February 27-March 2, 2006. International Fertilizer Industry Association, Paris, France.

As cited in Eagle et al. (2012), this may be a source of the "4R's" concept of nutrient management that was referenced in the first and third webinars. This concept has been widely used by a variety of commercial, governmental, and academic institutions.

Robertson, G.P. and P.M. Vitousek. 2009. Nitrogen in agriculture: Balancing the cost of an essential resource. *Annual Review of Environment and Resources*. 34:13.1-13.29.

A discussion of US N cycles and losses in relation to mitigating the impact of agricultural N on climate and the impact of climate on agricultural N.

Robertson, G.P., T.W. Bruulsema, R.J. Gehl, D. Kanter, D.L. Mauzerall, C.A. Rotz and C.O. Williams. 2013. Nitrogen-climate interactions in US agriculture. *Biogeochemistry*. 114:41-70.

Nitrogen is a crucial component of modern crop production yet a substantial amount that is added to cropping systems escapes to the environment. These losses can compromise the quality of air, land and water and can contribute to global climate change. This paper discusses approaches for reducing these losses and options for future research. It also discusses the potential impacts of climate change on N cycling, a topic not covered in these webinars.

Sehy, U., R. Ruser and J.C. Munch. 2003. Nitrous oxide fluxes from maize fields: Relationship to yield, site-specific fertilization, and soil conditions. *Agriculture, Ecosystems and the Environment*. 99:97-111.

Experimental study comparing N₂O emissions from areas of a corn field managed under high and low N applications, compared to strips that were managed under uniform N applications. There were no differences in N₂O emissions in the high yielding portions of the field, and N₂O emissions in the low yielding parts of the field were 34% lower when receiving variable rate N compared to uniform rate.

Six, J., S.M. Ogle, F.J. Breidt, R.T. Conant and K.H. Paustian. 2004. The potential to mitigate global warming with no-tillage management is only realized when practiced in the long term. *Global Change Biology*. 10:155-160.

For those interested in the impacts of tillage on N₂O emissions, see this review of the full global warming potential of changes from conventional tillage to no till. In the first 10 years, N₂O fluxes were higher in no till than conventional tillage. Over the long term (20 years), N₂O fluxes were lower in no till than conventional tillage in humid climates, and similar between tillage systems in dry climates.

Smart, D.R., M.M. Alsina, M.W. Wolff, M.G. Matiasek, D.L. Schellenberg, J.P. Edstrom, P.H. Brown, and K.M. Scow. 2011. N₂O emissions and water management in California perennial crops. p. 227–255. *In: Guo, L., Gunasekara, A.S., McConnell, L.L. (eds.), Understanding greenhouse gas emissions from agricultural management. American Chemical Society, Washington, DC.*

This chapter includes both a discussion of N₂O dynamics in agricultural systems, as well as summarizing the results of two field studies of N₂O emissions in irrigated perennial systems, one in a vineyard, and one in an almond orchard.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice and others. 2008. Greenhouse gas mitigation in agriculture. *Philosophical Transactions of the Royal Society B: Biological Sciences*. 363:789–813.

This is the academic paper that corresponds to the mitigation in agriculture chapter in the 2007 Intergovernmental Panel on Climate Change, Fourth Assessment Report. An updated report was released in spring of 2014, and is available at <http://www.ipcc.ch/>.

Snyder, C.S., T.W. Bruulsema, T.L. Jensen and P.E. Fixen. 2009. Review of greenhouse gas emissions from crop production systems and fertilizer management effects. *Agriculture Ecosystems and the Environment*. 133:247-266.

Reviews the effects of N source, rate, timing and placement in combination with other cropping and tillage practices on GHG emissions was conducted. Identifies specific strategies for minimizing losses based on review of scientific research outcomes.

Stehfest, E., and L. Bouwman. 2006. N₂O and NO emission from agricultural fields and soils under natural vegetation: Summarizing available measurement data and modeling of global annual emissions. *Nutrient Cycling in Agroecosystems*. 74:207-228.

This updates Bouwman et al. 2002. The IPCC Tier 1 approach (2006) for estimating N₂O fluxes from fertilizer application is based on this dataset, among others.

Stockle, C., S. Higgins, A. Kemanian, R. Nelson, D. Huggins, J. Marcos and H. Collins. 2012. Carbon storage and nitrous oxide emissions of cropping systems in eastern Washington: A simulation study. *Journal of Soil and Water Conservation*. 67:365-377.

The work summarized in this paper simulated the carbon benefit and N₂O impacts of conversion from conventional tillage to reduced- or no-till in three different dryland locations in eastern Washington with different amounts of annual rainfall (Lind, St. John, and Pullman), and one irrigated location (Paterson).

Suddick, E.C., K. Steenwerth, G.M. Garland, D.R. Smart and J. Six. 2011. Discerning agricultural management effects on nitrous oxide emissions from conventional and alternative cropping systems: A California case study. p. 203–226. *In*: Guo, L., Gunasekara, A.S., McConnell, L.L. (eds.), *Understanding greenhouse gas emissions from agricultural management*. American Chemical Society, Washington, DC.

A field study investigating the impact of irrigation management on N₂O emissions in an almond orchard.

Tullberg, J.N., D.F. Yule and D. McGarry. 2007. Controlled traffic farming-From research to adoption in Australia. *Soil and Tillage Research*. 97:272-281.

Reviews research evidence covering the impacts of wheel traffic on cropped soil, as well as the beneficial effects of controlled traffic farming. Also discusses the adoption of controlled traffic farming in Australia in extensive grain production and other farming systems.

US EPA. 2014. *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2012*. U.S. Environmental Protection Agency, Washington, D.C.

The most recent GHG inventory carried out by the U.S. Environmental Protection Agency. Includes estimates of the N₂O emissions from agricultural soils.

Vermeulen, G. and J. Mosquera. 2009. Soil, crop and emission responses to seasonal-controlled traffic in organic vegetable farming on loam soil. *Soil and Tillage Research*. 102:126-134.

A field study of the soil, crop, and N₂O emission responses of a vegetable farming system to seasonally controlled traffic (compared to random traffic with low ground pressures).

Veseth, R., R. McDole, C. Engle and J. Vomocil. 1989. No. 4, Fertilizer band location for cereal root access, in Chapter 6, Fertility management and fertilizer application. *In: Pacific Northwest conservation tillage handbook*. PNW Extension Series. University of Idaho, University of Washington, and Oregon State University, Moscow, ID.

Contains the drawing of a wheat plant used in the fertilizer banding slide in the third webinar.

WA Department of Ecology. 2010. Washington State greenhouse gas emissions inventory, 1990-2008. Department of Ecology, Olympia, WA. [Online]. Available at: http://www.ecy.wa.gov/climatechange/ghg_inventory.htm (verified 22 April 2014).

A recent GHG inventory done by Washington State. Includes estimates of N₂O emissions from agricultural soils. These estimates were updated in 2012 (report available at the website listed above), but the older report was used to allow for comparison with emissions in Oregon and Idaho.

Wagner-Riddle, C., Q.C. Hu, E. van Bochove and S. Jayasundara. 2008. Linking nitrous oxide flux during spring thaw to nitrate denitrification in the soil profile. *Soil Science Society of America Journal*. 72:908.

Field study from Canada exploring the mechanisms involved in high N₂O fluxes during freeze-thaw events.

Wrage, N., G.L. Velthof, M.L. van Beusichem and O. Oenema. 2001. Role of nitrifier denitrification in the production of nitrous oxide. *Soil Biology and Biochemistry*. 33:1723–1732.

While older, this review article has a fairly detailed but clear description of the different microbes involved in various alternative pathways that generate N₂O.

Zhu, X., M. Burger, T.A. Doane and W.R. Horwath. 2013. Ammonia oxidation pathways and nitrifier denitrification are significant sources of N₂O and NO under low oxygen availability. *Proceedings of the National Academy of Sciences*. 110:6328–6333.

Laboratory study of the importance of various pathways of N₂O production in fertilized agricultural soils.