# Baseline and example reductions in nitrous oxide emissions from agricultural land in Maryland

Prepared for

United States Department of Agriculture, Natural Resources Conservation Service

in partial fulfillment of the requirements of

Agreement No. 68-3B19-1-0018


By James B. Palmer (ICPRB) and William Angstadt (DMAA)

Interstate Commission on the Potomac River Basin and

Delaware-Maryland Agriculture Association



December 2012

ICPRB Report No. ICP 12-11

**ICPRB Report 12-11**

To receive copies of this report please contact

Interstate Commission on the Potomac River Basin
51 Monroe Street, Suite PE-08
Rockville, MD 20850

or call, 301-274-1908

**Disclaimer**

The opinions expressed in this report are those of the authors and should not be construed as representing the opinions or policies of the U. S. Government, the U. S. Department of Agriculture, Natural Resources Conservation Service, the several states, the signatories or Commissioners to the Interstate Commission on the Potomac River Basin.

Suggested citation for this report

Palmer, J.B. and W. Angstadt. 2012. Baseline and example reductions in nitrous oxide emissions from agricultural land in Maryland. ICPRB Report 12-11. Report prepared for the U. S. Department of Agriculture, Natural Resources Conservation Service in partial fulfillment of the requirements of Contract No. 68-3B19-1-0018.

Front cover: Corn. Photo by J.B. Palmer, ICPRB.

# Contents

List of Figures ... iii

List of Tables ... iii

Introduction ... 1

Literature review ... 1

Agricultural GHG emissions ... 1

GHG emission reduction credits ... 2

GHG emission models ... 3

Maryland agriculture and GHG emissions ... 3

Summary ... 4

Modeling ... 4

Model simulations ... 4

Modeling results ... 6

Discussion ... 7

Research Needs ... 8

Reduction credit trading ... 9

Acknowledgements ... 11

References ... 11

## List of Figures

Figure 1. Twelve year average $N_2O$ emissions by county, $MMtCO_2e$ ... 8

## List of Tables

Table 1. Fertilizer application rates, pounds per acre. ... 6

Table 2. Average $N_2O$ emissions by county for Baseline, 10% N reduced fertilizer, and 20% reduced fertilizer scenarios ($MMtCO_2e$) and average annual grain crop yield (kgC/ha/y). 7

Table 3. Average Baseline simulation results by county for the most recent 12 years. ... 9

Table 5. Average 20% reduction simulation results by county for the most recent 12 years. ... 11

# Introduction

Climate change as a result of accumulated greenhouse gases (GHG) could have several impacts on Maryland's environment and economy. Potential impacts include an increased risk in weather extremes (such as droughts, storms, flooding), heat-related stress, climate change related sea level rise, increased coastal erosion, and loss of usable land through inundation of coastal areas (MDE 2012a). In particular, Maryland is highly vulnerable to sea level rise as a result of climate change due to its extensive tidal coastline.

Among the GHGs released to the atmosphere as a result of human activities, nitrous oxide ($N_2O$) has 310 times the global warning potential of carbon dioxide ($CO_2$) (USEPA 2011). Emissions of $N_2O$ in agriculture are predominantly the result of anthropogenic soil management practices. On average, 1% of the nitrogen applied as fertilizer and manure is emitted as $N_2O$ into the atmosphere (GGWG 2010) producing 33% of the total $N_2O$ emissions in the U.S. (Snyder et al. 2007). In total, agricultural activities in Maryland contributed 2.3 million metric tons of greenhouse gas emissions (expressed as $CO_2$-equivalents, $MMtCO_2e$) in 2000 with 0.83 $MMtCO_2e$ from fertilizers and crops on agricultural soils and in 2005 a total of 1.8 $MMtCO_2e$ with 0.54 $MMtCO_2e$ from fertilizers and crops on agricultural soils (CCS 2008).

In 2009, Maryland passed the Greenhouse Gas Emission Reduction Act of 2009 requiring the state to develop and implement a plan to reduce GHG emissions by 25 percent from a 2006 baseline by 2020. One of the programs described in Maryland's Plan to Reduce Greenhouse Emissions (MDE 2012b) is Nutrient Trading for GHG Benefits. This program would add carbon credits and enhanced nutrient credits to the Maryland Nutrient Trading Program with an estimated reduction in GHG emissions of up to 0.21 $MMtCO_2e$ by 2020.

The purpose of this study is to assist NRCS in developing Chesapeake Bay Watershed Initiative programmatic guidance for reducing $N_2O$ emissions from agricultural land. The purpose was fulfilled utilizing a literature review and the simulation of GHG emissions under various cropping scenarios. The results of the study will be used to provide information necessary to accelerate the implementation of agricultural conservation practices that will reduce the level of $N_2O$ and other GHGs being released into the atmosphere from agricultural lands. Additional research needs in developing Maryland-specific emission factors are also identified.

# Literature review

The Interstate Commission on the Potomac River Basin (ICPRB) and the Delaware-Maryland Agriculture Association (DMAA) conducted a literature review of GHG emissions resulting from agricultural practices, protocols for issuing GHG reduction credits, greenhouse gas emission models, and studies applicable to Maryland climate and the impacts of farming practices in Maryland on GHG emissions.

## Agricultural GHG emissions

The U.S. Environmental Protection Agency conducted an inventory of emissions that identified and quantified the trends from 1990 through 2009 of the primary sources and sinks of anthropogenic greenhouse gases (USEPA 2011). In 2007, the International Plant Nutrition Institute (IPNI) (Snyder et al. 2007) conducted a literature review of the scientific literature on the linkages between nitrogen fertilizer use and GHG emissions. The findings from this review include 1) nitrogen fertilizer best management practices (BMPs) play a large role in minimizing residual soil nitrate which helps reduce the risk of $N_2O$ emissions; 2) site- and climate-specific conditions determine differences in $N_2O$ emissions among nitrogen fertilizer sources; and 3) intensive crop management systems do not necessarily increase GHG emissions per unit of food production, by helping keep natural areas from conversion to cropland and conversion of selected lands to afforestation for GHG mitigation through $CO_2$ sequestration. Smith and Conen (2004) reviewed the impacts of land use changes on the emissions of two greenhouse gases, methane ($CH_4$) and $N_2O$. One of the land use changes reviewed was the use of no-till agricultural practices as a way of increasing the sequestration of carbon. They found that in certain soil and climatic conditions there is an accompanying increase in $N_2O$ emissions. The American Society of Agronomy, the Crop Science Society of America, and the Soil Science Society of America produced a report summarizing current knowledge of GHG emissions as influenced by cropping system, tillage management, and nutrient source in six regions of the United States (GGWG 2010). The most effective way of reducing $N_2O$ emissions from agricultural lands is through increasing nitrogen-use efficiency (NUE). Methods to increase NUE include: perform site-specific soil tests to understand crop need; time fertilizer application to plant needs; use variable-rate technology; use crop monitoring and other technologies to apply nutrients based on actual crop need; and implement crop rotation using nitrogen-fixing cover crops to reduce the need to apply nitrogen fertilizers.

### GHG emission reduction credits

The Intergovernmental Panel on Climate Change in its Guidelines for National Greenhouse Gas Inventories (IPCC 2006) described methods and equations for estimating total national direct and indirect anthropogenic emissions of $N_2O$ from managed soils. The IPCC guidelines include the basic three-tier approach as used in the IPCC Good Practice Guidance for Land Use, Land-Use Change and Forestry (GPG-LULUCF) (IPCC 2003). This document provides guidance to estimate the emissions of greenhouse gases for each land use or land-use practice on a country basis including decision trees providing guidance on choices of method in terms of tiers. The tier structure used in the IPCC guidelines (Tier 1, Tier 2, and Tier 3) is hierarchical, with higher tiers (and tier numbers) implying increased accuracy of the method of estimating emissions factors and other parameters used in the estimation of the emissions. The guidelines (IPCC 2006) provide equations and default Tier 1 and Tier 2 emission factors, descriptions of methods and equations for estimating total national direct and indirect anthropogenic emissions of $N_2O$ from managed soils.

Several organizations have developed protocols for quantifying offsets in carbon dioxide equivalents for reductions of non-carbon dioxide GHGs (ACR 2010; Alberta Environment 2010; Diamant et al. 2011; Flederbach 2011; NRCS 2011; Haugen-Kozyra 2012; Heaney 2012; Janzen 2012; Millar et al. 2012). Carbon offsets make it possible for agricultural operators to participate in markets for GHG offsets through reductions in the amount of nitrogen and/or improving the efficiency of nitrogen amendments used to fertilize crops resulting in reductions in the amount of $N_2O$ emissions. These carbon offsets can be sold to other market participants to meet GHG emission reduction targets or requirements. The American Carbon Registry has developed a methodology which incorporates site specific data into a process-based computer model to calculate $N_2O$ emission reductions resulting from changes in how fertilizer is managed on a site-specific basis to calculate emission reductions (ACR 2010; Diamant et al. 2011). Another method, developed by Michigan State University (MSU) and the Electric Power Research Institute (EPRI) for the North Central Region of the U.S. and adopted by the American Carbon Registry, uses an equation developed for the North Central Region (NCR) of the U.S. to calculate the $N_2O$ emissions reductions for applicant projects in the NCR. Applicant projects in the U.S. outside the NCR use either a Tier 1 emission factor as defined by the IPCC (IPCC 2006) or a local project-supplied emissions factor (Millar et al. 2012).

### GHG emission models

Computer based models have been created to simulate the biogeochemistry of C and N in agricultural ecosystems (Li et al. 1992a; Li 1995; Li 2000; Li et al. 2006; DNDC 2007; Li 2007; Delgado et al. 2010a; Delgado et al. 2010b). Of interest to this study, these models can be used to simulate the impacts of agricultural practices such as nutrient application and cropping systems (Li et al. 1992b; Farahbakhshazad et al. 2008; Li et al. 2010; Smith et al. 2010; Olander and Haugen-Kozyra 2011). The Denitrification-Decomposition (DNDC) model is a process based model that simulates the biogeochemistry of the soil, climate, crops, and agronomic activities and the nitrification, denitrification and fermentation processes to simulate the nitric oxide (NO), $N_2O$, dinitrogen ($N_2$), $CH_4$, and ammonia ($NH_3$) fluxes within the agricultural ecosystem (DNDC 2007). Simulations can be performed specific to local agriculture sites or on regional estimates of agricultural activities. The DNDC model was used to estimate GHG emission factors for changes in agricultural management in Canada (Smith et al. 2010). DNDC was used to simulate the impacts of alternative agricultural management practices on crop yield and various greenhouse gas emissions from a row-crop field in Iowa (Farahbakhshazad et al. 2008). The Nitrogen Loss and Environmental Assessment Package (NLEAP)[1] model simulates soil carbon and nitrogen processes in the soil including processes for water and nitrate fluxes; surface runoff of water, nitrate, ammonium; nitrate leaching from the root zone; crop uptake of nitrate and ammonium; denitrification losses; and ammonia volatilization (Shafer et al. 2010). Delgado et al. (2010a) report using NLEAP to evaluate agricultural management practices in Colorado, Ohio and Virginia. Data required by these computer models include, but are not limited to, climate (temperature, precipitation, etc.), soils (texture, pH, bulk density, etc.), farming management practices (cropping systems and durations, etc.), tillage, fertilization, manure amendment, and irrigation (DNDC 2007; Delgado et al. 2010b). Outputs from the models include C and N fluxes and water budget in the agroecosystem (DNDC 2007; Delgado et al. 2010b). As a part of their research on $N_2O$ emissions, MSU (McSwiney 2010) has expanded and refined an online "carbon calculator" to estimate GHG emissions by county for major grain crops using inputs of crop yield, tillage, fertilizer application rate, using an IPCC (2006) Tier 1 emission factor, described below. This calculator is based on the SOCRATES (Soil Organic Carbon Reserves And Transformations in EcoSystems) soil carbon model (Grace et al. 2006).

### Maryland agriculture and GHG emissions

The Maryland Department of the Environment developed a plan to achieve the 25 percent GHG reduction required under the Greenhouse Gas Emission Reduction Act of 2009 while also creating jobs and improving Maryland's economy (MDE 2012a). One of the programs identified in the plan calls for the Maryland Department of Agriculture to expand the Nutrient Trading Program to included trading in GHG credits (MDE 2012a; MDE 2012b).

In the Northeast region it appears there are no studies quantifying GHG emissions in agricultural systems. No studies were found of GHG emissions response to agricultural practices specific to Maryland and few

---

[1] Nitrogen Loss and Environmental Assessment Package with GIS capabilities (NLEAP GIS 4.2), U.S. Department of Agriculture, Agricultural Research Service, https://www.ars.usda.gov/services/software/download.htm?softwareid=292 accessed March 20, 2012.

in the Mid-Atlantic region (NWCC 2012). One Mid-Atlantic study used the NLEAP model to evaluate various no-till crop rotations in two soil textures in Virginia (Delgado et al. 2008). Long-term field experiments and data collection are needed to quantify the $N_2O$ emissions baseline and reductions resulting from implementing various practices in order to determine GHG benefits so that these benefits can be successfully registered in a carbon trading market (GGWG 2010).

### Summary

Emissions of GHGs from agricultural lands and their linkages to nitrogen fertilizer use have been studied in the U.S. and worldwide. Agricultural practices have been studied for their effects on emissions of GHGs including $N_2O$. A standard emission factor was developed to estimate GHG emission rates on a country-wide scale. Protocols have been developed to quantify the $N_2O$ emissions from agricultural lands in the North Central Region of the U.S. using this standard $N_2O$ emission factor. These protocols are designed to allow for the creation of carbon-equivalent $N_2O$ emission reduction credits that can be exchanged on carbon trading markets. Computer-based models are available to study the GHG emission response of agricultural systems to changes in environmental conditions and agricultural management practices. Once calibrated and validated these models can be used to estimate the change in GHG emissions resulting from proposed adjustments in agricultural practices and provide verification of local or site scale emission factors. Validation of regional, local, or site scale emission factors depends on scale-dependent data about the climate, soil, and typical agricultural practices. Detailed studies compiling this data and the GHG emission responses applicable to Maryland have not been published.

## Modeling

By quantifying the $N_2O$ emissions baseline and any emissions reductions resulting from implementing various agricultural management practices, the resulting GHG emissions benefits can be determined. The benefits can then be registered in a carbon registry (e.g. American Carbon Registry, Climate Action Reserve, etc.). The IPCC has developed Tier 1 default emission factors (IPCC 2006) for estimating GHG emissions at the national level, but these estimates become less appropriate as the spatial resolution decreases from the regional level to local and site levels. Combined with the a lack of detailed studies of GHG emissions response to agricultural practices in Maryland developers of GHG mitigation programs or protocols have to use the Tier 1 default GHG emission factors developed by IPCC (2006). Biogeochemical model simulations can be used to improve the accuracy of this quantification of GHG reduction emission factors resulting from the implementation of alternative agricultural practices.

### Model simulations

Version 9.2 of DNDC was used to perform simulations of the biogeochemistry of agricultural systems in order to simulate the emission of $N_2O$ in response to adjustments in the application of nitrogen fertilizers to corn crops in Maryland. The model program and associated data were obtained from the DNDC Biogeochemistry Model web site[2]. There are many inputs required for the model including parameters related to climate, soil properties, vegetation, and anthropogenic activities. Outputs from each simulation include fluxes of $CO_2$, $CH_4$, $NH_3$, NO, $N_2O$, $N_2$, and crop yield. Simulations assumed a corn crop and utilized parameter values for the dominant soil type under normal climate conditions and typical crop

[2] DNDC web site at: http://www.dndc.sr.unh.edu/, accessed April 12, 2012.

practices by county. A separate text file with the input parameters unique to each county was generated plus a text file containing a list of the county input files. This text file was used to run DNDC in batch mode, with the model performing the simulation for each county in turn. The outputs were recorded in separate simulation summary files for each county.

Climate input data for the simulations were taken from a 22-year (1984-2005) continuous time series of hourly precipitation data developed from a statistical analysis of rainfall data observed at numerous measurement stations in the Mid-Atlantic region prepared for and used in the Chesapeake Bay Program Phase 5.3 Community Watershed Model[3]. Hourly precipitation data were summed to provide daily precipitation values and hourly air temperature data were used to calculate mean daily temperatures for each county. Estimates of the rate of atmospheric deposition of nitrate were also taken from the Chesapeake Bay Program Phase 5.3 Community Watershed Model on a monthly and yearly basis[4] and were used to assign nitrate atmospheric deposition input values for each county. All scenarios used a simulation period of 24 years following the method described in Delgado et al. (2010a) using the 22 years of available climate data. The first 3 years (1982, 1983 and 1984) of simulation used climate data from 1984. The remaining years used the contemporaneous climate data. Twenty two years of climate data were used to provide a fairly complete range of likely climate conditions. Also following Delgado et al. (2010a), only the last 12 years of simulation results were averaged for each county.

Default values of most soil characteristics were taken from the U.S. Greenhouse Gas Wizard data sets, a version of the DNDC model[5] with U.S. specific data sets. Soil texture and clay fraction input parameters for each county were generated based on the dominant soil type classification in the SSURGO datasets[6]. The dominant soil type was determined using a GIS to determine the total area of each soil type in the county. This approach however, does not relate the dominant soil type with the actual land area used for crop production.

Corn is the dominant crop in Maryland, occupying 40% of the harvested cropland (USDA 2009). Therefore, corn was the single crop input for the model runs. Default values of crop parameters for corn from the DNDC 9.2 data sets were used in all simulations due to the lack of Maryland-specific values. Multiple simulation scenarios were run using different rates of nitrogen fertilizer application. For the Baseline scenario a total of 150 pounds per acre (lb/ac) (168 kilograms per hectare [kg/ha]) nitrogen fertilizer was applied three times during each year, 30 lb/ac (34 kg/ha) at planting on April 20$^{th}$ and 60 lb/ac (67 kg/ha) on May 1$^{st}$ and June 15$^{th}$ (Table 1). Two additional scenarios were run with reduced application of fertilizer using a reduction of 10% and 20% respectively applied on the same dates.

---

[3]Precipitation and air temperature data inputs for the Chesapeake Bay Phase 5.3 Community Watershed Model from: http://ches.communitymodeling.org/models/CBPhase5/datalibrary/meteorological-data.php and documented at ftp://ftp.chesapeakebay.net/modeling/P5Documentation/SECTION_2.pdf, accessed March 8, 2012.

[4]Atmospheric deposition data inputs for the Phase 5.3 model from: ftp://ftp.chesapeakebay.net/Modeling/phase5/Phase%205.3%20Calibration/Model%20Input/AtmosDepP53CalibrationInputSummary.xls , accessed March 8, 2012.

[5] Soil parameter data from the US Greenhouse Gas Wizard: http://www.dndc.sr.unh.edu/, accessed February 2, 2012.

[6] SSURGO data for each county in Maryland from: http://soils.usda.gov/survey/geography/ssurgo/, accessed July 12, 2012.

**Table 1. Fertilizer application rates, pounds per acre.**

| Scenario | Baseline | 10% Reduction | 20% Reduction |
|---|---|---|---|
| 1st Application | 30 | 27 | 24 |
| 2nd Application | 60 | 54 | 48 |
| 3rd Application | 60 | 54 | 48 |

## Modeling results

Simulation results for each year and a summary of all years were recorded for each county from each simulation scenario. Each county's average values for the most recent 12 years of the simulations were calculated for each of seven fluxes; change in SOC (Soil Organic Carbon) (dSOC, kgC/ha/y), Grain Yield (GrainC_yield, kgC/ha/y), N uptake (N_uptake, kgN/ha/y), $N_2O$ emission ($N_2O$, kgN/ha/y), $NH_3$ emission ($NH_3$ kgN/ha/y), total precipitation (Total Precip mm), and mean temperature (Mean T °C) (Tables 3, 4, and 5). The DNDC model generates estimates of GHGs in kilograms per hectare per year. The 12-year average values of $N_2O$ emissions from the model were converted to per acre and applied to the total acres of cropland planted in corn in each county. The acres of cropland in corn were obtained from the 1992, 1997, 2002, and 2007 USDA Ag Census for Maryland (USDA 1999; USDA 2004; USDA 2009) and estimates of the acres of corn cropland for the intervening years were calculated by linear interpolation. The 12-year average acres of cropland in corn for grain were used in the calculation of 12-year average $N_2O$ emissions. Table 2 shows the simulated 12-year average $N_2O$ emissions, in $MMtCO_2e$, for each county and the Maryland total.

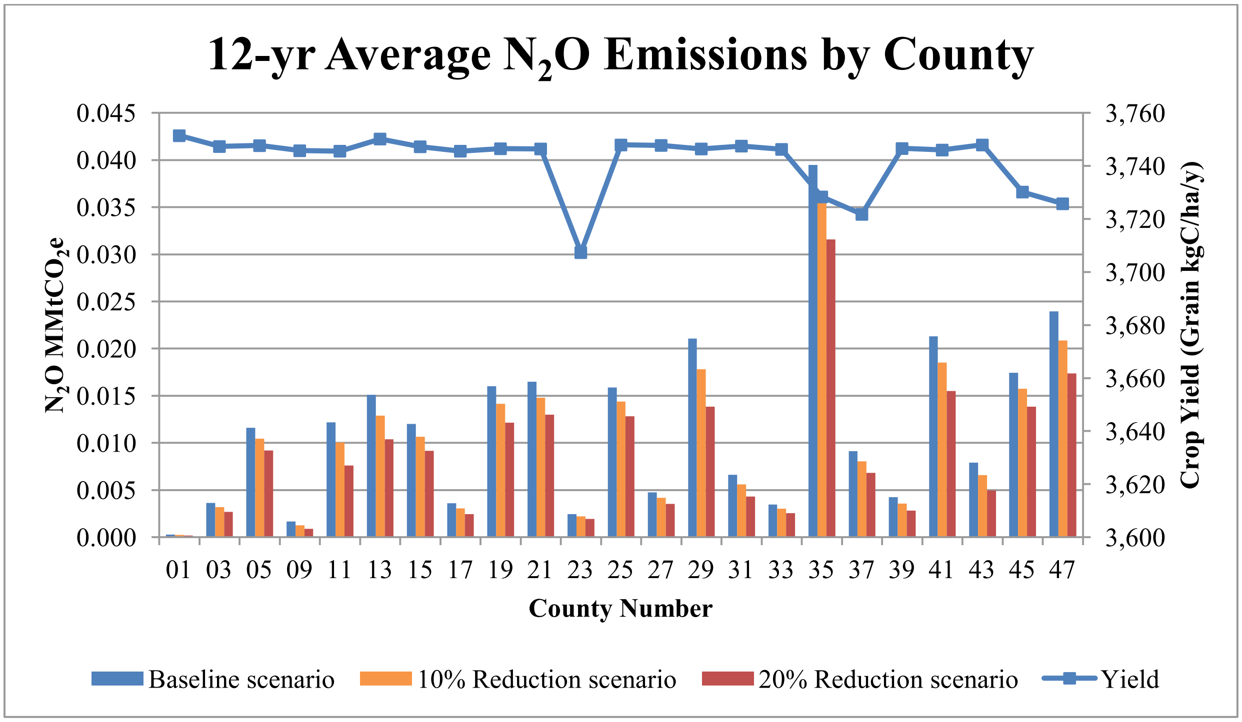
**Table 2. Average $N_2O$ emissions by county for Baseline, 10% N reduced fertilizer, and 20% reduced fertilizer scenarios ($MMtCO_2e$).**

| County | Average Acres Corn for Grain (ac) | Baseline ($MMtCO_2e$) | 10% Reduction Scenario ($MMtCO_2e$) | Emission Reduction (%) | 20% Reduction Scenario ($MMtCO_2e$) | Emission Reduction (%) | County Number |
|---|---|---|---|---|---|---|---|
| Allegany | 496 | 0.0003 | 0.0002 | 15% | 0.0002 | 32% | 01 |
| Anne Arundel | 5,277 | 0.0036 | 0.0032 | 13% | 0.0027 | 27% | 03 |
| Baltimore County | 15,199 | 0.0116 | 0.0104 | 10% | 0.0092 | 21% | 05 |
| Calvert | 4,305 | 0.0017 | 0.0013 | 24% | 0.0009 | 47% | 09 |
| Caroline | 25,355 | 0.0122 | 0.0101 | 17% | 0.0076 | 38% | 11 |
| Carroll | 30,590 | 0.0151 | 0.0129 | 15% | 0.0104 | 31% | 13 |
| Cecil | 19,390 | 0.0120 | 0.0106 | 11% | 0.0092 | 24% | 15 |
| Charles | 5,506 | 0.0036 | 0.0031 | 15% | 0.0025 | 31% | 17 |
| Dorchester | 21,942 | 0.0160 | 0.0141 | 12% | 0.0122 | 24% | 19 |
| Frederick | 20,296 | 0.0165 | 0.0148 | 10% | 0.0130 | 21% | 21 |
| Garrett | 4,505 | 0.0024 | 0.0022 | 9% | 0.0020 | 20% | 23 |
| Harford | 20,734 | 0.0159 | 0.0144 | 9% | 0.0128 | 19% | 25 |
| Howard | 7,475 | 0.0048 | 0.0042 | 12% | 0.0036 | 25% | 27 |
| Kent | 39,903 | 0.0211 | 0.0178 | 15% | 0.0139 | 34% | 29 |
| Montgomery | 11,936 | 0.0066 | 0.0056 | 16% | 0.0043 | 35% | 31 |
| Prince Georges | 4,922 | 0.0035 | 0.0030 | 13% | 0.0025 | 27% | 33 |
| Queen Anne's | 48,835 | 0.0395 | 0.0357 | 9% | 0.0316 | 20% | 35 |
| St. Mary's | 12,281 | 0.0091 | 0.0080 | 12% | 0.0068 | 25% | 37 |
| Somerset | 8,992 | 0.0042 | 0.0036 | 16% | 0.0028 | 34% | 39 |
| Talbot | 33,172 | 0.0213 | 0.0185 | 13% | 0.0155 | 27% | 41 |
| Washington | 15,480 | 0.0079 | 0.0066 | 17% | 0.0050 | 37% | 43 |
| Wicomico | 21,810 | 0.0174 | 0.0157 | 10% | 0.0139 | 21% | 45 |
| Worchester | 37,940 | 0.0239 | 0.0209 | 13% | 0.0174 | 27% | 47 |
| Maryland Total | 416,339 | 0.2703 | 0.2369 | 12% | 0.1997 | 26% | |

## Discussion

Simulations of GHG emissions were performed using a peer-reviewed process based biogeochemical model (DNDC) with average climate, soil, and agricultural management input parameters for each county in Maryland. A Baseline and two reduced nitrogen fertilizer application scenarios were run to evaluate the potential $N_2O$ emissions reductions. Crop yield, reported as the carbon content of the grain harvested, for each county was the same between the 10% and 20% reduced nitrogen fertilizer application scenarios and the Baseline scenario with one exception. There was a slight increase of less than 1% in the reported grain yield for Calvert County in both 10% and 20% reduced fertilizer scenarios compared to the Baseline scenario. The 10% reduced fertilizer application scenario produced a median reduction in $N_2O$ emissions for all counties relative to the Baseline scenario simulation of 13% and the 20% reduced fertilizer application scenario resulted in a median reduction in $N_2O$ emissions for all counties relative to the Baseline scenario of 27 percent (Figure 1 and Table 2).

**Figure 1. Twelve year average $N_2O$ emissions by county, $MMtCO_2e$**




These simulation results suggest that reducing the amount of applied nitrogen fertlizer will result in a significant reduction in $N_2O$ emissions from agricultural land planted in corn  in most counties in Maryland while at the same time not reducing the crop yield.  However, since default parameter values for agricultural management practices, soil characteristics, and climate conditions were used in the simulations, similar results are likely to be achievable using combinations of nitrogen reductions and other management practices.

## Research Needs

The results of this study indicate that considerably more research needs to be conducted before $N_2O$ emissions factors or an emissions reduction crediting program can be implemented in Maryland.  $N_2O$ emissions are correlated with soil pH, mineral N, temperature, pore moisture, organic carbon, soil compaction, and many other environmental factors. There is significant underlying uncertainty in the appropriate Maryland-specific values of all these input parameters used in the model simulations. Calibration and validation of the model inputs under the broad spectrum of climate condition, soil type, and agricultural practice parameters for all agricultural regions in Maryland must be performed.  The applicability of each of these factors to actual agricultural conditions and conservation practices in Maryland must be evaluated.  Data collection and in-field research to allow validation of a Tier 1 emission factor or Tier 2 type emission factors for each county or agricultural region of Maryland need to be developed.  Ultimately, emission factors for the whole state, for each county, or for each agricultural region in Maryland need to be developed to allow for the implementation of GHG emissions reduction credits in a credit trading program.

### Reduction credit trading

One of the objectives of this project was to determine a procedure for registering credits on a voluntary carbon market. Under the Greenhouse Gas Emission Reduction Act of 2009 Maryland's Nutrient Trading Program will be expanded to include trading credits for reductions in GHG emissions. The Nutrient Trading Program was initiated in 2007 to be a public marketplace for the buying and selling of credits for the reduction of nutrients released to the ground water and surface waters of the state. The steps remaining in order to allow the issuance and trading of $N_2O$ reduction credits are several. First, appropriate emission factors need to be developed for the baseline and alternative agricultural management practices in agricultural settings throughout Maryland. Next, these emission factors will need to be verified, requiring considerable research and field data collection efforts. Then, agricultural projects could apply for emission reduction credits. Finally, credit issuing agencies (e.g. MDA, USDA/NRCS, etc.) would perform a technical review of the application and if approved, certify the credits and list them as available for trading within the Maryland Nutrient Trading Program or other similar programs.

**Table 3. Average Baseline simulation results by county for the most recent 12 years.**

| County | dSOC KgC/ha | GrainC_yield kgC/ha/y | N_uptake kgN/ha/y | $N_2O$ kgN/ha/y | $NH_3$ kgN/ha | Total Precip mm | MeanT °C |
|---|---|---|---|---|---|---|---|
| Allegany | -187 | 3751 | 136 | 4.6 | 0.1 | 966 | 11.3 |
| Anne Arundel | -204 | 3747 | 135 | 5.5 | 0.1 | 1082 | 13.8 |
| Baltimore County | -191 | 3748 | 135 | 6.1 | 0.1 | 1090 | 12.6 |
| Calvert | -205 | 3746 | 135 | 3.1 | 0.0 | 1099 | 13.8 |
| Caroline | -209 | 3746 | 135 | 3.8 | 0.0 | 1143 | 13.8 |
| Carroll | -196 | 3750 | 135 | 3.9 | 0.1 | 1083 | 11.6 |
| Cecil | -190 | 3747 | 135 | 4.9 | 0.1 | 1121 | 12.6 |
| Charles | -205 | 3746 | 135 | 5.2 | 0.1 | 1060 | 14.1 |
| Dorchester | -212 | 3747 | 135 | 5.8 | 0.1 | 1122 | 14.3 |
| Frederick | -199 | 3746 | 135 | 6.5 | 0.1 | 1052 | 13.4 |
| Garrett | -178 | 3707 | 134 | 4.3 | 0.2 | 1201 | 8.6 |
| Harford | -187 | 3748 | 135 | 6.1 | 0.1 | 1107 | 12.4 |
| Howard | -198 | 3748 | 135 | 5.1 | 0.1 | 1067 | 12.4 |
| Kent | -199 | 3746 | 135 | 4.2 | 0.1 | 1129 | 13.5 |
| Montgomery | -197 | 3748 | 135 | 4.4 | 0.1 | 1050 | 12.6 |
| Prince Georges | -202 | 3746 | 135 | 5.6 | 0.1 | 1040 | 13.4 |
| Queen Anne's | -242 | 3728 | 135 | 6.4 | 0.1 | 1139 | 13.7 |
| St. Mary's | -245 | 3722 | 134 | 5.9 | 0.1 | 1104 | 14.3 |
| Somerset | -180 | 3747 | 135 | 3.8 | 0.1 | 1155 | 14.5 |
| Talbot | -209 | 3746 | 135 | 5.1 | 0.1 | 1127 | 14.0 |
| Washington | -193 | 3748 | 135 | 4.1 | 0.0 | 1016 | 12.1 |
| Wicomico | -258 | 3730 | 135 | 6.4 | 0.1 | 1143 | 14.0 |
| Worchester | -235 | 3726 | 134 | 5.0 | 0.1 | 1126 | 13.6 |

**Table 4. Average 10% fertilizer reduction simulation results by county for the most recent 12 years.**

| County | dSOC KgC/ha | GrainC_yield kgC/ha/y | N_uptake kgN/ha/y | $N_2O$ kgN/ha/y | $NH_3$ kgN/ha | Total Precip mm | MeanT °C |
|---|---|---|---|---|---|---|---|
| Allegany | -187 | 3751 | 136 | 3.9 | 0.1 | 966 | 11.3 |
| Anne Arundel | -202 | 3747 | 135 | 4.8 | 0.1 | 1082 | 13.8 |
| Baltimore County | -191 | 3748 | 135 | 5.5 | 0.1 | 1090 | 12.6 |
| Calvert | -205 | 3747 | 135 | 2.4 | 0.0 | 1099 | 13.8 |
| Caroline | -208 | 3746 | 135 | 3.2 | 0.0 | 1143 | 13.8 |
| Carroll | -196 | 3750 | 135 | 3.4 | 0.1 | 1083 | 11.6 |
| Cecil | -190 | 3747 | 135 | 4.4 | 0.1 | 1121 | 12.6 |
| Charles | -204 | 3746 | 135 | 4.4 | 0.1 | 1060 | 14.1 |
| Dorchester | -211 | 3747 | 135 | 5.1 | 0.1 | 1122 | 14.3 |
| Frederick | -199 | 3746 | 135 | 5.8 | 0.1 | 1052 | 13.4 |
| Garrett | -178 | 3707 | 134 | 3.9 | 0.2 | 1201 | 8.6 |
| Harford | -187 | 3748 | 135 | 5.5 | 0.1 | 1107 | 12.4 |
| Howard | -199 | 3748 | 135 | 4.5 | 0.1 | 1067 | 12.4 |
| Kent | -198 | 3746 | 135 | 3.6 | 0.1 | 1129 | 13.5 |
| Montgomery | -195 | 3748 | 135 | 3.7 | 0.1 | 1050 | 12.6 |
| Prince Georges | -202 | 3746 | 135 | 4.9 | 0.1 | 1040 | 13.4 |
| Queen Anne's | -242 | 3728 | 135 | 5.8 | 0.1 | 1139 | 13.7 |
| St. Mary's | -244 | 3722 | 134 | 5.2 | 0.1 | 1104 | 14.3 |
| Somerset | -178 | 3747 | 135 | 3.2 | 0.1 | 1155 | 14.5 |
| Talbot | -208 | 3746 | 135 | 4.5 | 0.1 | 1127 | 14.0 |
| Washington | -192 | 3748 | 135 | 3.4 | 0.0 | 1016 | 12.1 |
| Wicomico | -257 | 3730 | 135 | 5.7 | 0.1 | 1143 | 14.0 |
| Worchester | -233 | 3726 | 134 | 4.4 | 0.1 | 1126 | 13.6 |

Table 4. Average 20% fertilizer reduction simulation results by county for the most recent 12 years.

| County | dSOC KgC/ha | GrainC_yield kgC/ha/y | N_uptake kgN/ha/y | $N_2O$ kgN/ha/y | NH3 kgN/ha | Total Precip mm | MeanT °C |
|---|---|---|---|---|---|---|---|
| Allegany | -187 | 3751 | 136 | 3.1 | 0.1 | 966 | 11.3 |
| Anne Arundel | -203 | 3747 | 135 | 4.0 | 0.1 | 1082 | 13.8 |
| Baltimore County | -190 | 3748 | 135 | 4.8 | 0.1 | 1090 | 12.6 |
| Calvert | -204 | 3753 | 135 | 1.6 | 0.0 | 1099 | 13.8 |
| Caroline | -208 | 3746 | 135 | 2.4 | 0.0 | 1143 | 13.8 |
| Carroll | -196 | 3750 | 135 | 2.7 | 0.1 | 1083 | 11.6 |
| Cecil | -190 | 3747 | 135 | 3.8 | 0.1 | 1121 | 12.6 |
| Charles | -203 | 3746 | 135 | 3.6 | 0.1 | 1060 | 14.1 |
| Dorchester | -209 | 3747 | 135 | 4.4 | 0.1 | 1122 | 14.3 |
| Frederick | -199 | 3746 | 135 | 5.1 | 0.1 | 1052 | 13.4 |
| Garrett | -178 | 3707 | 134 | 3.5 | 0.2 | 1201 | 8.6 |
| Harford | -187 | 3748 | 135 | 4.9 | 0.1 | 1107 | 12.4 |
| Howard | -197 | 3748 | 135 | 3.8 | 0.1 | 1067 | 12.4 |
| Kent | -197 | 3746 | 135 | 2.8 | 0.0 | 1129 | 13.5 |
| Montgomery | -194 | 3748 | 135 | 2.9 | 0.0 | 1050 | 12.6 |
| Prince Georges | -200 | 3746 | 135 | 4.1 | 0.1 | 1040 | 13.4 |
| Queen Anne’s | -242 | 3728 | 135 | 5.2 | 0.1 | 1139 | 13.7 |
| St. Mary’s | -245 | 3722 | 134 | 4.4 | 0.1 | 1104 | 14.3 |
| Somerset | -179 | 3747 | 135 | 2.5 | 0.1 | 1155 | 14.5 |
| Talbot | -208 | 3746 | 135 | 3.7 | 0.1 | 1127 | 14.0 |
| Washington | -191 | 3748 | 135 | 2.6 | 0.0 | 1016 | 12.1 |
| Wicomico | -258 | 3730 | 135 | 5.1 | 0.1 | 1143 | 14.0 |
| Worchester | -231 | 3726 | 134 | 3.6 | 0.1 | 1126 | 13.6 |

## Acknowledgements

The authors would like to thank Olivia Devereux, formerly with ICPRB, for being instrumental in initiating this project. The authors also thank Donna Giltrap from Landcare Research and Pete Ingraham from Applied GeoSolutions, LLC for assistance in setting up and developing the DNDC simulations. Funding for this project was provided by the United States Department of Agriculture Natural Resources Conservation Service. Editorial review and improvements were generously provided by Heidi Moltz of ICPRB.

## References

Alberta Environment. 2010. Quantification protocol for agricultural nitrous oxide emissions reductions, version 1.0. Province of Alberta, Edmonton, AB. 99p.

ACR. 2010. American Carbon Registry methodology for $N_2O$ emission reductions through changes in fertilizer management. Winrock International, Little Rock, AR. 58p.

Bruulsema, T. W. and Q. Ketterings. 2008. Best management for fertilizers on Northeastern dairy farms. International Plant Nutrition Institute, Norcross, GA. 8p.

CCS, 2008, Maryland climate action plan Appendix C, Final Maryland greenhouse gas inventory and reference case projections 1990-2020, Appendix F - Agriculture. Center for Climate Strategies, Washington, DC. 7p.

Delgado, J.A., M.J. Shaffer, H. Lal, S.P. McKinney, C.M. Gross, and H. Cover. 2008. Assessment of nitrogen losses to the environment with a nitrogen trading tool (NTT). Comput. Electron. Agric. 63:193-206.

Delgado, J.A., C.M. Gross, H. Lal, H. Cover, P. Gagliardi, S.P. McKinney, E. Hesketh, and M.J. Shaffer. 2010a. A new GIS nitrogen trading tool concept for conservation and reduction of reactive nitrogen losses to the environment *in* D.L. Sparks, (Ed.), Advances in Agronomy. Burlington: Academic Press. 105:117-171.

Delgado, J.A., P.M. Gagliardi, D. Neer, and M.J. Shaffer. 2010b. Nitrogen loss and environmental assessment package with GIS capabilities (NLEAP-GIS 4.2): User Guide. USDA-ARS, Fort Collins, CO. 141p.

Diamant, A., G.P. Robertson, N. Millar, and R.J. Gehl. 2011. Creating nitrous oxide ($N_2O$) emissions offsets in agricultural crop production in the United States (aka "Nutrient Management"), background paper for the EPRI Greenhouse Gas Emissions Offset Policy Dialogue Workshop #11, November, 2011. 33p.

DNDC. 2007. User's guide for the DNDC model (version 9.1). Institute for the Study of Earth, Oceans and Space, University of New Hampshire. 61p.

FAO. 2001. Global estimates of gaseous emissions of $NH_3$, NO and $N_2O$ from agricultural land. Food and Agriculture Organization of the United Nations or the International Fertilizer Industry Association. FAO and IFA. Rome. 66p.

Farahbakhshazad, N., D.L. Dinnes, C. Li, D.B. Jaynes, W. Salas. 2008. Modeling biogeochemical impacts of alternative management practices for a row-crop field in Iowa. Agriculture, Ecosystems and Environment. 123(1-3):30-48.

Flederbach, W.E. Jr. 2011. $N_2O$ abatement protocol. Clime Co. Boyertown, PA. 25p.

Grace, P.R., J.N. Ladd, G.P. Robertson, and S.H. Gage. 2006. SOCRATES: A simple model for predicting long-term changes in soil organic carbon in terrestrial ecosystems. Soil Biol. Biochem. 38:1172–1176.

Greenhouse Gas Working Group (GGWG). 2010. Agriculture's role in greenhouse gas emissions and capture. Greenhouse Gas Working Group Rep. ASA, CSSA, and SSSA, Madison WI. 16p.

Haugen-Kozyra, K. 2012. NERPinar: Nitrous oxide emissions reduction protocol (NERP), an overview. Presented at NERPinar, March 28, 2012. Canadian Fertilizer Institute, Ottawa, ON. 10p.

Heaney, D. 2012. NERPinar: Nitrous oxide emissions reduction protocol (NERP), What's under the hood? Presented at NERPinar, March 28, 2012. Canadian Fertilizer Institute, Ottawa, ON. 33p.

Institute for Policy Integrity. 2011. Long overdue: EPA and nitric acid plant regulation. New York. 22p.

IPCC. 2003. Good practice guidance for land use, land-use change and forestry. J. Penman, Gytarsky, T. Hiraishi, T. Krug, D. Kruger, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe, F. Wagner (Eds.).Intergovernmental Panel on Climate Change (IPCC), IPCC/IGES, Hayama, Japan.

IPCC. 2006. Intergovernmental panel on climate change guidelines for national greenhouse gas inventories. Volume 4: Agriculture, forestry and other land use. Chapter 11: $N_2O$ emissions from managed soils, and $CO_2$ emissions from lime and urea application. http://www.ipcc-nggip.iges.or.jp/public/2006gl/pdf/4_Volume4/V4_11_Ch11_$N_2O$&$CO_2$.pdf accessed 3/15/2012.

Janzen, R. 2012. NERPinar: Context and development of the NERP. Presented at NERPinar, March 28. 2012. Canadian Fertilizer Institute, Ottawa, ON. 9p.

Lewandrowski, J., C. Jones, R. House, M. Peters, M. Sperow, M. Eve, and K. Paustian. 2004. Economics of sequestering carbon in the U.S. agricultural sector. Technical Bulletin 1909. USDA. Washington, DC. 69p.

Li, C.S. 1995. Modeling impact of agricultural practices on soil C and $N_2O$ emissions. *in* Soil Management and Greenhouse Effect, R. Lal, J. Kimble, E. Levine, and B.A. Stewart (Eds.). CRC Press, Boca Raton, FL. 14p.

Li, C.S., 2000. Modeling trace gas emissions from agricultural ecosystems. Nutrient Cycling in Agroecosystems, 58: 259-276.

Li, C.S., 2007. Quantifying greenhouse gas emissions from soils: Scientific basis and modeling approach. Soil Science and Plant Nutrition, 53: 344–352.

Li, C., S. Frolking, T.A. Frolking. 1992a. A model of nitrous oxide evolution from soil driven by rainfall events: 1. Model structure and sensitivity. J. Geophys. Res. 97(D9): 9759-9776.

Li, C., D. Frolking, T.A. Frolking. 1992b. A model of nitrous oxide evolution from soil driven by rainfall events: 2. Model applications. J. Geophys. Res. 97(D9): 9777-9783.

Li, C., N. Farahbakhshazad, D.B. Jaynes, D.L. Dinnes, W. Salas, D. McLaughlin. 2006. Modeling nitrate leaching with a biogeochemical model modified based on observations in a row-crop field in Iowa. Ecological Modeling, 196:116-130.

Li, H., J. Qiu, L. Wang, H. Tang, C. Li, E. Van Ranst. 2010. Modeling impacts of alternative farming management practices on greenhouse gas emissions from a winter wheat–maize rotation system in China. Agriculture, Ecosystems and the Environment, 135: 24-33.

McSwiney, C.P., S. Bohm, P.R. Grace, and G.P. Robertson. 2010. Greenhouse gas emissions calculator for grain and biofuel farming systems, in revision. J. Nat. Resour. Life Sci. Educ. 39: 125–13.

MDE. 2012a. Maryland's plan to reduce greenhouse gas emissions: A plan to reduce GHG emissions and produce a net economic benefit to Maryland's economy, Maryland Department of the Environment. 367p.

MDE. 2012b. Maryland's plan to reduce greenhouse gas emissions, December 31, 2011 – Appendix C Maryland climate change programs, Maryland Department of the Environment. 380p.

Millar, N., G.P. Robertson, A. Diamant, R.J. Gehl, P.R. Grace, and J.P. Hoben. 2012. Methodology for quantifying nitrous oxide ($N_2O$) emissions reductions by reducing nitrogen fertilizer use on agricultural crops. American Carbon Registry, Winrock International, Little Rock, AR.

NRCS. 2011. Natural resources credit trading reference. USDA NRCS, Washington, DC. 79p.

NWCC. 2012. Climate information retrieval for Maryland. USDA NRCS National Water and Climate Center, http://www.wcc.nrcs.usda.gov/cgibin/state.pl?state=md, accessed 3/13/2012.

Olander, L.P., K. Haugen-Kozyra. 2011. Using biogeochemical process models to quantify greenhouse gas mitigation from agricultural management projects. Nicholas Institute for Environmental Policy Solutions, Report NI R 11-03. 35p.

Shafer, M.J., J.A. Delgado, C.M. Gross, R.F. Follett, P. Gagliardi. 2010. Simulation processes for the nitrogen loss and environmental assessment package. *in* Delgado, J.A., and R.F. Follett, (Eds.) Advances in Nitrogen Management for Water Quality. Soil and Water Conservation Society, Ankeny, IA. 361-372.

Smith, K. A. and F. Conen. 2004. Impacts of land management on fluxes of trace greenhouse gases. Soil Use and Management, 20: 255-263.

Smith, P., D. Martino, Z. Cai, D. Gwary, H. Janzen, P. Kumar, B. McCarl, S. Ogle, F. O'Mara, C. Rice, B. Scholes, O. Sirotenko, M. Howden, T. McAllister, G. Pan, V. Romanenkov, U. Schneider, S. Towprayoon, M. Wattenbach and J. Smith. 2008. Greenhouse gas mitigation in agriculture. Phil. Trans. R. Soc. B, 363: 89–813.

Smith, W.N., B.B., Grant, R.L. Desjardins, D. Worth, C. Li, S.H. Boles, E.C. Huffman. 2010. A tool to link agricultural activity data with the DNDC model to estimate GHG emission factors in Canada. Agric., Ecosyst. Environ, 136(3-4):301-309.

Snyder, C.S., T.W. Bruulsema, and T.L. Jensen. 2007. Greenhouse gas emissions from cropping systems and influence of fertilizer management - a literature review. International Plant Nutrition Institute, Norcross, GA. 36p.

Snyder, S.C. 2008. Fertilizer nitrogen BMPs to limit losses that contribute to global warming. International Plant Nutrition Institute, Norcross, GA. 8p.

USDA. 1999. 1997 Census of agriculture, National Agricultural Statistics Service, Maryland, State and County Data. Vol. 1, Chapter 2, Table 13. Selected crops harvested: 1997 and 1992. U.S. Department of Agriculture, Washington, DC. 4p.

USDA. 2004. 2002 Census of agriculture, National Agricultural Statistics Service, Vol. 1. Geographic Area Series, Part 51. U.S. Department of Agriculture, Washington, DC. 663p.

USDA. 2009. 2007 Census of agriculture, National Agricultural Statistics Service, Maryland, State and County Data. Vol. 1. U.S. Department of Agriculture, Washington, DC. 475p.

USEPA. 2011. Inventory of U.S. greenhouse gas emissions and sinks:1990 – 2009, EPA 430-R-11-005. U.S. Environmental Protection Agency, Washington, D.C. 459p.