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# Assessment of alternative soil management practices on $N_2O$ emissions from US agriculture

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**Abstract**

Although agricultural soil management is the predominant anthropogenic source of nitrous oxide ($N_2O$) to the atmosphere, little is known about the effects of alternative soil management practices on $N_2O$ emissions. In this study the NGAS model of Parton et al. (1996), coupled with a N and C cycling model, was used to simulate annual $N_2O$ emissions from 2639 cropland sites in the US using both no-till and conventional tillage management scenarios. The $N_2O$ mitigation potential of returning marginal cropland to perennial grass was also evaluated by comparing simulated $N_2O$ emissions from 306 Conservation Reserve Program (CRP) grassland sites with emissions from nearby cropland sites. Extensive soil and land use data for each site was obtained from the Natural Resource Inventory (NRI) database and weather data was obtained from NASA. The initial conversion of agricultural land to no-till showed greater $N_2O$ emissions per hectare than conventional tillage. Differences between the two tillage scenarios were strongly regional and suggest that conversion of conventionally tilled soil to no-till may have a greater effect on $N_2O$ emissions in drier regions. About 80% of the total emissions were from the Great plains and central regions mainly due to their large cultivated area. Croplands producing soy, wheat, and corn were responsible for about 68% of the total emissions with rice, cotton, and vegetable croplands having the greatest $N_2O$ flux (6.5–8.4 kg $N_2O$–N $ha^{-1}$ $year^{-1}$) under either scenario. Model simulations estimate that the agricultural lands in the US produce 448 Gg $N_2O$–N $year^{-1}$ under a conventional tillage scenario and 478 Gg $N_2O$–N $year^{-1}$ under a no-till scenario. Model estimates also suggest that the conversion of 10.5 million hectares of cropland to grassland has a $N_2O$ mitigation potential of 31 Gg $N_2O$–N $year^{-1}$, (8.4 Tg carbon equivalents $year^{-1}$). This value is similar in magnitude to many of the major greenhouse gas (GHG) emission-reduction strategies currently being considered to help meet US GHG reduction goals. Thus the GHG mitigation potential of this conversion is substantial and may be a viable strategy to help meet GHG reduction goals. 

*Keywords:* Nitrous oxide; CRP; Tillage; Denitrification; Nitrification; Greenhouse gases

## 1. Introduction

Nitrous oxide ($N_2O$) is a long lived atmospheric trace gas that influences the climate as a greenhouse gas (GHG) (Dickenson and Cicerone, 1986) and

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participates in the formation and destruction of stratospheric ozone (Cicerone, 1987). Atmospheric $N_2O$ levels have risen approximately 15% since pre-industrial times (Prather et al., 1994), because of biotic and anthropogenic activities, and the gas may eventually contribute to as much as 10% of the global warming potential (Cicerone, 1989). In order for atmospheric concentrations to be stabilized near current levels anthropogenic sources need to be reduced by more than 50% (Prather et al., 1994).

There are many sources of $N_2O$ but soil is believed to be the predominant source, contributing about 70% of the total $N_2O$ emitted from the biosphere into the atmosphere (Bouwman, 1990). $N_2O$ is produced in soil primarily by two dissimilar energy producing microbial processes, nitrification and denitrification. $N_2O$ production by both processes is regulated by complex interactions between N availability, soil moisture and oxygen status, and soil type, texture, pH, and organic carbon content.

$N_2O$ derived from the agricultural soil management is poorly quantified but probably contributes to over 75% of total anthropogenic $N_2O$ emissions (Cole et al., 1996). Agricultural soil management practices, including tillage, irrigation, and fertilizer usage, affect $N_2O$ emissions by altering soil structure and N-cycling characteristics. Although emissions from this source may be amenable to reduction with changes in soil management practices (Cole et al., 1996; Mosier et al., 1996b) little information is available about the effect of alternative management practices, such as no-till management and returning marginal cropland to perennial grass, on $N_2O$ flux at regional scales.

Cultivation of marginal land enhances both soil degradation and GHG emissions (Lal et al., 1995). Marginal lands in the US account for about 25% of rural non-federal land and about 25% of this land was used for cropland in 1982 (USDA, 1989). The availability of low-cost fertilizer and fuel has allowed much of this land to be brought into, and kept in, production. US government programs that promote land use changes, such as the Conservation Reserve Program (CRP), may be a means to reduce GHG emissions. The CRP was implemented in 1985 with the goal of removing 18 million of the 55 million hectares of land designated as highly erodible from crop production and revegetating them with grass or trees.

Assessing the effects of management practices, such as tillage or grasslands, on $N_2O$ emissions at regional scales is currently hampered by lack of methodology to accurately estimate regional $N_2O$ emissions. Williams et al. (1992) recommended that process-level models be developed that can simulate the complex interactions between the many biotic and abiotic variables that regulate $N_2O$ production in the soil at all relevant spatial and temporal scales. Parton et al. (1996) recently developed such a model that is a hybrid between detailed process oriented models (Li et al., 1992) and simplistic nutrient cycling models (Parton et al., 1988).

If the input data to these types of models is specific and detailed enough then the model can estimate flux at any point in space where this data is available. The objective was to obtain detailed soil property and land use data and couple the NGAS model of Parton et al. (1996) with a N and C cycling model to simulate $N_2O$ emissions for cropland and grassland sites throughout the US. The goals of this study were to estimate total $N_2O$ emissions from cropland in the US, to evaluate $N_2O$ emissions under no-till and conventional tillage scenarios, and to evaluate the $N_2O$ mitigation potential of returning marginal cropland to perennial grass associated with the CRP.

## 2. Model input and description

Model input included National Resource Inventory (NRI) soils data for soil organic matter content, textural properties, pH, moisture contents at field capacity and the wilting point, average monthly temperatures, and land use for 2639 cropland and 306 CRP sites in the continental US.

The NGAS model was designed to be incorporated into nitrogen cycling models and used to simulate regional and global trace gas production as a function of climate, soil properties, and management practices. The model was developed using laboratory denitrification gas flux data (Weier et al., 1993) and field-observed $N_2O$ flux data (Mosier et al., 1996a). To date this model is the most sophisticated, well calibrated and widely used model for gas flux estimations, details of this model can be found in Parton et al. (1996); Mosier et al. (1997).

The NGAS model estimates nitrification $N_2O$ flux as a function of soil texture, $NH_4^+$ content, water-filled pore space (WFPS), N turnover rate, pH, and temperature. Total denitrification gas fluxes ($N_2$+$N_2O$) are calculated as a function of soil respiration rates (C availability), $NO_3^-$ content, WFPS, and texture. Estimates of denitrification $N_2O$ flux are calculated using a function of total denitrification gas fluxes, soil respiration rate, soil $NO_3^-$ concentration, and WFPS.

To calculate daily $NH_4^-$ availability for nitrification and plant uptake, and C-availability for denitrification, a modified decomposition model from Molina et al. (1983); Li et al. (1992) was used that allowed for decomposition to occur simultaneously and independently in plant residue, microbial biomass, and organic matter pools. Each pool has labile and resistant fractions that were assigned specific decomposition rates for optimal conditions (Li et al., 1992). Decomposition rates were then reduced under conditions of N limitation, non-optimum soil moisture and temperature, and increasing clay content.

Plant nitrogen requirements at each site were removed daily over the growing season from soil $NH_4^+$ and $NO_3^-$ pools based on their relative concentrations. Representative soil N plant extraction rates, timing, and amounts, for each specific crop, were obtained from the literature (Olson and Kurtz, 1982; Buyanovsky et al., 1987). The plant residue pool was gradually released for decomposition 1 month before the end of the growing season to simulate the natural senescence of plant components. All decomposable residues were then added to the decomposable residue pool.

Nitrification rates and $NO_3^-$ availability for denitrification and plant uptake were calculated as a function of soil moisture content, soil temperature, and $NH_4^+$ availability with optimal rates at 35°C and WFPS of 90% (Li et al., 1992).

A one dimensional soil moisture model was used to calculate WFPS for each day of the year. For each one hour time step water fluxes were determined by gradients of soil water potential. Unsaturated hydraulic conductivity was calculated for each site using the method of Campbell (1974). Representative values for saturated hydraulic conductivity ($K_s$) and the water content at saturation ($\theta_s$) for each soil textural class were obtained from Clapp and Hornberger (1978).

Precipitation data was obtained from NASA (1983) for weather stations across the US providing monthly precipitation and the number of days each month having precipitation greater than 2.54 mm. Daily addition of water to the soil was determined by dividing the average monthly precipitation by the number of days each month having precipitation greater than 2.54 mm. These fractions were then added to the soil at equal intervals throughout the month after subtracting daily losses to evapotranspiration (ET) as calculated by Li et al. (1992).

### 2.1. Cropland parameterization

Crops used were corn, sorghum, soybeans, wheat, oats, rice, barley, cotton, peanuts, tobacco, vegetables, sunflowers, hay, and idle cropland. Plant residue amounts for each cropland site were obtained from the NRI data base.

For non-leguminous cropland $NH_4^+$ was added to the inorganic-N pool 1 week before planting. Wheat, oats, barley, rice, and sorghum received 60 kg N $ha^{-1}$, corn 150 kg N $ha^{-1}$, cotton 80 kg N $ha^{-1}$ and vegetable crops 100 kg N $ha^{-1}$ in the spring and 100 kg N $ha^{-1}$ in the autumn. Leguminous crops generally have lower C/N ratios than non-leguminous crops, and therefore biological N-fixation was accounted for by allocating lower C/N ratios to the leguminous crop residue pool.

Conventional tillage practices are known to enhance surface soil organic matter decomposition rates. Since most agricultural land in US has been under cultivation for 50 years or more the method Kern and Johnson (1993) was used to calculate SOM losses from use of conventional tillage practices. This method assumes that, on an average, US agricultural soils have lost 75% of the SOM that will be lost and that an additional 10% will be lost in the next 30 years with continued tillage. At the time of each tillage, twice yearly spring and autumn, organic matter from the resistant SOM pool was transferred to the labile SOM pool and made available for decomposition.

Much research indicates that no-till soils generally have enhanced surface soil water holding capacity compared with conventionally tilled soils (Doran, 1980). In US Doran (1980) found that no-tilled soils had, on average, 1.4 times greater surface moisture than conventionally tilled soils. Therefore, for the no-till scenario soil water contents were increased by 40% over that of the conventional tillage scenario.

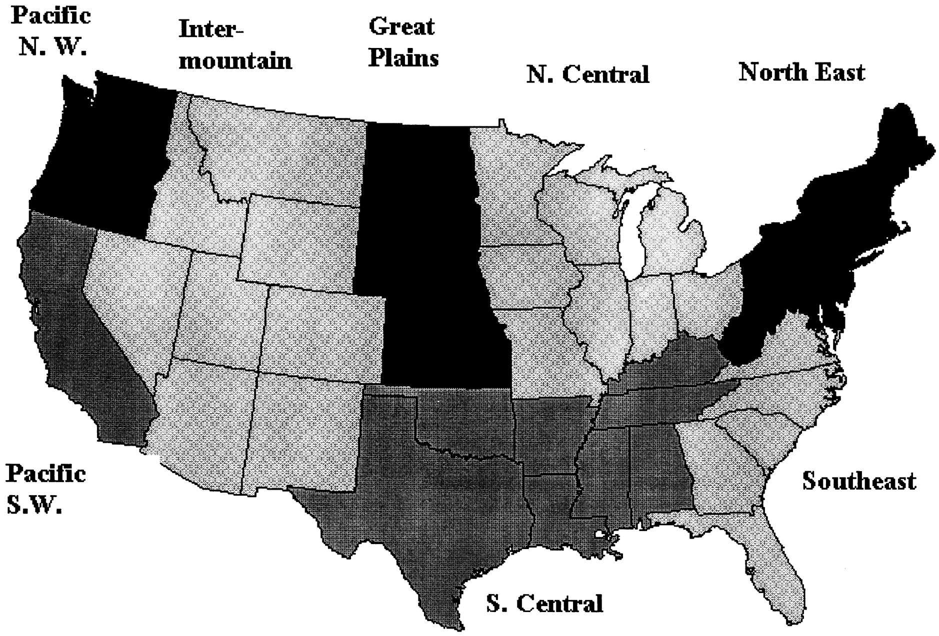


Fig. 1. Regions used for estimating cropland $N_2O$ emissions.

Site and crop specific $N_2O$ flux can be useful to develop local management strategies to reduce GHG emissions. However, for larger scale estimates it is necessary to integrate the data base. The continental US was therefore divided into eight regions based on the similarity of climate (Fig. 1). The regional $N_2O$ flux for each crop type in each region is the product of the regional land area (USDA, 1996) of each crop and the mean annual $N_2O$ flux for the crop in the region. This calculation captures the two main attributes of regional $N_2O$ flux estimates, climate and major crop.

### 2.2. Grassland parameterization

The average grass biomass of the standing crop produced at each site was calculated using annual precipitation, usable solar incident radiation and a stepwise multiple regression equation generated by Sims et al. (1978) and used for yearly plant residue inputs.

The annual $N_2O$ emission reduction from the conversion of cropland to CRP grassland at each site was calculated as the difference between the total emission at the CRP grassland site and the average emissions from all cropland sites within 0.3° latitude and longitude of each CRP site. The average $N_2O$ emission of nearby cropland sites, rather than regional estimates, was used for these calculations in order to ensure that the soil and the climate characteristics of cropland and CRP grassland sites were as similar as possible. In addition, this method of calculation incorporates the localized effects of crop rotations on emissions into the estimates. $N_2O$ flux reduction in each region was determined by multiplying the regional CRP land area (USDA, 1996) by the average annual reduction in $N_2O$ flux for all sites in the region.

## 3. Results and discussion

### 3.1. Agricultural $N_2O$ emissions

Table 1 presents the simulated annual $N_2O$–N fluxes and the ratio of no-till to conventional tillage $N_2O$ fluxes for all crop types. Since numerous sites for each crop were modeled the mean, median and coefficient of variation (CV) are presented to provide information on the location and shape of the distribution of

Table 1
Annual $N_2O$–N flux for all crop types and tillage practices

| Crop | Annual $N_2O$–N flux Mean (kg ha$^{-1}$ year$^{-1}$) | Median | C.V.[a] (%) | Number of sites |
|---|---|---|---|---|
| *Corn* | | | | |
| Ct[b] | 2.9 | 2.4 | 95.5 | 1035 |
| Nt[c] | 3.6 | 3.6 | 45.5 | 1035 |
| Nt/Ct[d] | 1.9 | 1.5 | | |
| *Sorghum* | | | | |
| Ct | 4.8 | 2.5 | 106.2 | 69 |
| Nt | 3.0 | 2.5 | 75.8 | 69 |
| Nt/Ct | 2.2 | 1.5 | | |
| *Soy* | | | | |
| Ct | 4.6 | 4.0 | 63.8 | 655 |
| Nt | 4.9 | 4.7 | 45.5 | 655 |
| Nt/Ct | 1.7 | 1.3 | | |
| *Cotton* | | | | |
| Ct | 6.5 | 4.9 | 76.6 | 160 |
| Nt | 7.0 | 7.0 | 59.2 | 160 |
| Nt/Ct | 1.5 | 1.4 | | |
| *Peanuts* | 6.2 | 5.5 | 59.8 | 16 |
| *Tobacco* | | | | |
| Ct | 4.6 | 3.6 | 103.4 | 13 |
| Nt | 3.4 | 4.3 | 76.4 | 13 |
| Nt/Ct | 1.3 | 1.4 | | |
| *Vegetable Row crops* | | | | |
| Ct | 6.5 | 3.5 | 86.5 | 26 |
| Nt | 6.9 | 4.4 | 73.2 | 26 |
| Nt/Ct | 1.3 | 1.3 | | |
| *Sunflowers* | | | | |
| Ct | 1.9 | 2.0 | 12.7 | 6 |
| Nt | 3.9 | 3.9 | 11.1 | 6 |
| Nt/Ct | 2.0 | 2.0 | | |
| *Wheat* | | | | |
| Ct | 4.8 | 3.3 | 89.7 | 467 |
| Nt | 4.6 | 4.4 | 51.6 | 467 |
| Nt/Ct | 1.5 | 1.5 | | |
| *Oats* | | | | |
| Ct | 3.8 | 2.4 | 104.3 | 39 |
| Nt | 4.2 | 3.8 | 65.2 | 39 |
| Nt/Ct | 1.5 | 1.6 | | |
| *Rice* | | | | |
| Ct | 7.6 | 5.8 | 93.9 | 35 |
| Nt | 8.4 | 6.0 | 82.0 | 35 |
| Nt/Ct | 1.1 | 1.0 | | |
| *Barley* | | | | |
| Ct | 4.0 | 2.3 | 107.5 | 73 |
| Nt | 4.4 | 3.4 | 83.8 | 73 |
| Nt/Ct | 1.7 | 1.5 | | |

[a] C.V., coeffient of variation×100%.
[b] Ct, conventional tillage.
[c] Nt, no-tillage.
[d] Nt/Ct was calculated as the mean of the site ratios.

simulated values. The highest simulated $N_2O$ fluxes were from rice, cotton, and vegetable row croplands. These crops are predominantly grown in warm humid regions that receive relatively large amounts of precipitation or are irrigated (rice, vegetable row crops) or receive high fertilizer inputs (cotton, 80 kg N ha$^{-1}$ year$^{-1}$; vegetable row crops, 200 kg N ha$^{-1}$ year$^{-1}$).

The no-till scenario had, on average, greater $N_2O$ flux per hectare than the conventional tillage scenario. The ratio of no-till to conventional tillage $N_2O$–N flux for individual crop types ranged from 1.3 for tobacco to 2.0 for sunflowers with the average ratio over all crops being 1.6 (Table 1). These results are consistent with other studies suggesting that no-till or reduced tillage systems generally have higher $N_2O$ emission rates than plowed fields (Linn and Doran, 1984; Gilliam and Hoyt, 1987).

The higher emissions exhibited by reduced tillage are generally considered to result from the physical, chemical, and biological changes in the soil environment associated with reduced soil disturbance. The lack of soil disturbance with reduced tillage leads to a reduction in large pores (Lal, 1976), increased soil aggregation (Doran, 1980; Beare et al., 1994) higher moisture levels and water-filled pore space (Doran, 1980; Linn and Doran, 1984), and reduced aeration (Dowdell et al., 1979). In addition, greater root growth near the surface, (Ellis et al., 1979) greater soil organic C and N (Blevins et al., 1983; Beare et al., 1994), and significantly greater surface microbial biomass (Carter and Rennie, 1982) are generally associated with reduced tillage. Populations of bacteria responsible for $N_2O$ production may also be greater under no-till management. Doran (1980) found surface (0–7.5 cm) populations of denitrifiers and $NH_4^+$ and $NO_2^-$ oxidizers to be 7.31, 1.25, and 1.58 times greater respectively, in no-till soils than in tilled soils.

Table 2
Regional cropland areas and the total mean annual $N_2O$–N emissions for conventional and no-tillage cropping systems

| Region | Cropland ($ha \times 10^6$) | Conventional tillage | No-tillage |
|---|---|---|---|
| | | $N_2O$–N ($kg \times 10^6$ $year^{-1}$) | |
| Northeastern | 5 | 6.0 | 7.8 |
| Northcentral | 50 | 152.6 | 164.0 |
| Great plains | 29 | 86.6 | 86.2 |
| Inter-mountain | 11 | 20.5 | 40.0 |
| Pacific NW | 3 | 6.0 | 7.0 |
| Pacific SW | 3 | 12.5 | 11.2 |
| Southcentral | 31 | 140.0 | 134.0 |
| Southeastern | 7 | 24.0 | 27.0 |

On a regional basis the no-till scenario resulted in an increased $N_2O$ emissions in the Pacific northwest, intermountain, northcentral, northeast, and southeastern regions (Table 2) suggesting that the increased soil moisture associated with no-till systems takes precedence over the increased SOM decomposition rates associated with conventional tillage in these regions. This is most evident in the relatively dry Intermountain region where the no-till emissions were about twice that from conventional tillage. Total $N_2O$ emissions were lower for the no-till scenario in the southwest and southcentral regions and similar to the conventional tillage scenario for the Great plains region. These results suggest that extensive conversion from conventional tillage management to no-till management may not be a viable $N_2O$ mitigation strategy as suggested by Li et al. (1996).

$N_2O$ fluxes for both tillage scenarios were generally higher from the eastern and central regions (northcentral, northeast, southeast, southcentral, and Great plains) where the soil and the climatic conditions are more favorable for $N_2O$ production. The combined emissions from the Great plains, northcentral, and southcentral regions amounted to 84% of the total conventional tillage scenario and 80% of the total no-till scenario because of their large crop areas and relatively high $N_2O$ flux. Due to their preponderance the greatest contribution to total emissions were from soybeans, wheat, and corn, which together accounted for about 70% of the total emissions from either tillage system. The distribution of $N_2O$ production estimates suggest that $N_2O$ quantification and mitigation efforts may be most effective if focused on soy, corn, and wheat production in the Great plains, central and the eastern regions.

$N_2O$–N emissions for all US agricultural lands totalled 448 Gg $N_2O$–N $year^{-1}$ for the conventional tillage scenario based on the mean $N_2O$ flux and 347 Gg $N_2O$–N $year^{-1}$ based on the median $N_2O$ flux. For the no-till scenario the emissions totalled 478 Gg $N_2O$–N $year^{-1}$ based on the mean $N_2O$ flux and 448 Gg $N_2O$–N $year^{-1}$ based on the median $N_2O$ flux.

These model based estimates fail to account for the indirect emissions from fertilizer N. Indirect emissions from fertilizer N are all emissions that can be attributed to fertilizer N that occur apart from the field where fertilizer N is applied. Mosier et al. (1996b) estimated that 0.75% of N applications will eventually reach the atmosphere as off-site $N_2O$ emissions resulting from N leaching, runoff and $NO_x$ and $NH_3$ volatilization. This could be a significant source considering that 10.3 Tg fertilizer N is applied yearly in US

### 3.2. *$N_2O$ emissions from CRP grasslands*

Table 3 presents simulated annual regional reductions in $N_2O$ emissions due to conversion of marginal cropland to CRP grassland on a hectare basis and total regional $N_2O$ emission reductions. The average reductions in $N_2O$ emissions per hectare in the eight regions ranged from 2.1 kg $N_2O$–N ha $year^{-1}$ in the relatively dry and cool region of north and south Dakota to 5.3 kg $N_2O$–N ha $year^{-1}$ in the relatively warm and wet region of CRP land in Texas.

From the regional estimates the total annual reduction in $N_2O$ emissions from this conversion is about 31 Gg $N_2O$–N, equaling about 8.4 Tg carbon equivalents $year^{-1}$. Current official US policy is to reduce US GHG emissions by 108 Tg carbon equivalents $year^{-1}$ by the year 2000 (U.S. Department of State, 1994). Thus the benefit from reductions in $N_2O$ emissions attributable to cropland conversion may meet about 7.7% of this goal each year. The estimate for CRP grassland $N_2O$ mitigation potential is similar to many of the major GHG mitigation strategies outlined in US Climate Action Plan (U.S. Department of State, 1994).

$N_2O$ mitigation benefits should be immediate after conversion to perennial grass because of cessation of N-fertilization, but may also be dependent on the time the land is planted in perennial grass and future

Table 3
Regional areas of CRP grassland, average annual reduction of $N_2O$ emissions due to conversion of cropland to CRP grassland and the total reduction in $N_2O$ emissions for each region

| Regional states | CRP area ($ha \times 10^6$) | Emission reduction (kg $N_2O$–N $ha^{-1}$ $year^{-1}$) | Total emission reduction (Gg $N_2O$–N $year^{-1}$) |
|---|---|---|---|
| Washington Idaho Oregon | 0.9 | 3.2 | 2.9 |
| Montana Wyoming | 1.2 | 2.2 | 2.6 |
| North Dakota South Dakota | 1.7 | 2.1 | 3.4 |
| Minnesota | 0.7 | 2.7 | 1.8 |
| Iowa Missouri | 2.4 | 2.6 | 6.2 |
| Nebraska Kansas | 1.6 | 3.9 | 6.5 |
| Colorado New Mexico | 1.4 | 3.3 | 4.5 |
| Texas | 0.6 | 5.3 | 3.3 |
| Total | 10.5 | | 31.2 |

management. Mosier et al. (1997) found that in a shortgrass steppe ecosystem $N_2O$ emissions required between 8 and 50 years to return to rates similar to an adjacent native grassland site that had never been subjected to tillage or N-fertilization. These authors also found that tillage of native grassland resulted in $N_2O$ emissions 8 times higher than an adjacent native grassland for about 18 months following tillage and 25–50% higher 2–3 years later. This suggests that part of the $N_2O$ mitigation benefit of the CRP would be lost if returned to a tillage-based cropping system because of enhanced decomposition of SOM-N resulting in $N_2O$ emissions.

The current study includes only 80% of the total area enrolled in the CRP. Current CRP area comprises only 27% of the 55 million hectares of land designated as highly erodible in US suggesting that the potential to mitigate GHG emissions from highly erodible croplands in the United States is substantial.

## 4. Conclusion

Estimates of the $N_2O$ flux from agricultural cropland and grasslands are virtually unattainable due to the paucity of field measured $N_2O$ flux. Basic process models offer reasonable estimates of $N_2O$ flux if detailed soil and weather input data for multiple sites is used. This study has shown the usefulness of this approach in comparing different management systems for agricultural land.

Concern about soil quality has stimulated interest in finding alternatives to tillage-based agricultural management practices. Reduced tillage agriculture is an important means to maintain soil quality and sequester atmospheric $CO_2$ in soil. The results here suggest that no-till management in areas that are relatively warm and wet may result in $N_2O$ emissions similar to or less than conventional tillage and that no-till management may be a viable means to reduce $N_2O$ emissions while increasing soil quality. Conversely, simulated $N_2O$ emissions were greater for no-till systems in drier regions, because of increased soil moisture. Therefore, no-till management may not be a viable $N_2O$ mitigation strategy in drier areas.

Although overall $N_2O$ emissions were greater for initial conversion to no-till the greater $N_2O$ flux maybe short lived and simply the result of the non-equilibrium of the changing system. Over time as the crop residues increase the active fraction of the SOM pool the N cycling may become tighter and less available to be converted to gas. The increase in SOM and N sequestration may be even more prominent in the more arid soils because of the initial low SOM pools.

Marginal or unsustainable cropland maybe better used for growing perennial grass or trees as in CRP land. It has been recognized that this type of land utilization can improve surface and groundwater quality (Huang et al., 1990), increase wildlife habitat (Kantrud, 1993), improve air quality (Ribaudo et al., 1989), preserve soil productivity and soil quality (Burke et al., 1995) as well as return the land to a condition that supports forage production. The results of this study show that it also has the added benefit of mitigating the environmental effects of anthropogenic GHG by reducing $NO_2$ emissions.

Based on these results land use and management are the important considerations in designing a GHG mitigation strategy for the US.

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