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Assessment of potential for development of a simplified methodology for accounting for reduction in N_2O emissions from change in fertilizer usage

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WINROCK INTERNATIONAL

EXECUTIVE SUMMARY

Nitrogen fertilizers represent the dominant cause of greenhouse gas emissions from agricultural crop production. In 2007 nitrous oxide from agricultural soil management was responsible for 3.4% of net US emissions.

The purpose of the study was to develop a methodology that could be used to calculate emission reduction offsets from activities associated with nitrogen-based fertilizers in US agriculture. To have credibility in the developing carbon market the methodology would have to accurately represent the impact on the atmosphere and would involve the input of significant site-specific data. Thus the Intergovernmental Panel on Climate Change (IPCC)'s Tier 1 approach is far from sufficient as it simply multiplies the quantity applied by defaults to calculate emissions. Yet a methodology must not be excessively expensive to implement as it would preclude the possibility of any project being implemented thus direct measurement of nitrous oxide from fields using measurement chambers could not be considered.

A methodology was chosen for testing that included site specific information on type of fertilizer, soil carbon concentration, drainage, pH, soil texture and crop type. The highly parameterized, tested and peer-reviewed model DNDC (Denitrification-Decomposition) was used to estimate the "real" atmospheric impact at the test sites.

Test sites were chosen in Arkansas (cotton), Iowa (corn) and California (lettuce) for the 2009 growing season. The sites were visited for measurements of relevant soil characteristics and data were collected from the farmers on fertilizer usage, yield and irrigation.

The more parameterized simple model produced estimates that were closer to reality than the IPCC Tier 1 approach but still diverged dramatically from results modeled by DNDC. The principle reason for the divergence is the lack of the capability of the simple model to deal with the seasonality in water availability (both from irrigation and rainfall) and temperature.

Neither the IPCC Tier 1 method nor the new method proposed here based on Bouwman et al (2002) are sufficient for an offset project methodology that would be able to evaluate atmospheric impact of a broad range on fertilizer management practices. Therefore alternative approaches must be considered.

The three methods were used to compare the net consequences for greenhouse gas emissions of 12 different potential changes in fertilizer management. The changes included four scenarios for changes in fertilizer quantity, two for fertilization depth, four for fertilization timing and two for nitrification inhibitors. This comparison highlighted a further weakness of the simplified models; the simplified models can only evaluate the impacts of changes in quantify of fertilizer applied not in the methods of application.

The recommendation arising from this report is to develop an offset methodology based on the application of DNDC for projects. A DNDC methodology will require expertise but atmospheric integrity is better guaranteed, monitoring would likely be inexpensive and costs would be low considering that offset projects are likely to consist of aggregations of large numbers of farms.

CONTENTS

ACKNOWLEDGEMENTS

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1.0 INTRODUCTION

Changing farming practices is one of the most effective ways to reduce emissions of gases with high global warming potential into the atmosphere. In particular, improved farming practices can play a critical role in addressing nitrous oxide (N_2O) emissions, as agricultural use of nitrogen fertilizer constitutes the main source of this potent greenhouse gas. Therefore, adjustments to farm practices are among the most cost-effective ways to reduce emissions of large amounts of N_2O into the atmosphere, a gas that is 310 times more potent for global warming than CO_2.

In 2007 nitrous oxide from agricultural soil management was responsible for 3.4% of net US emissions. Emissions direct from synthetic fertilizer use were equal to 47.3 Tg CO_2 Eq, indirect emissions from croplands added an additional 24.9 Tg CO_2 Eq. The total emissions resulting from fertilizer use on US croplands was therefore 72.2 Tg CO_2 Eq in 2007 or 1.2% of net US emissions. Nitrous oxide is produced naturally in soils through the processes of nitrification and denitrification. Nitrification is the aerobic microbial oxidation of ammonium to nitrate, and denitrification is the anaerobic microbial reduction of nitrate to nitrogen gas (N_2). Nitrous oxide is a gaseous intermediate in the reaction sequence of denitrification and a by-product of nitrification that leaks from microbes into the soil and ultimately into the atmosphere. One of the main controlling factors in this reaction is the availability of inorganic N in the soil.

Excessive use of nitrogen in agricultural systems not only contributes to greenhouse gas emissions but also impairs water quality, reduces biodiversity and threatens human health. The voluntary market for reducing greenhouse gas emissions can be used to stimulate improved fertilizer management practices that can both achieve the desired business objectives of owners and investors and benefit the environment. To “commoditize” these ecosystem services, a transparent accounting framework is necessary that can be administered cost effectively. Transparency is essential to the success of a market-based approach. It ensures credible quantification of the environmental benefits achieved by each activity and allows market players to undertake trades of known commodities. The costs of measurement and verification must be reasonable relative to the value of the benefits.

The IPCC has issued guidelines for reporting N_2O emissions under national greenhouse gas inventories, and EPA has adapted these guidelines for use in preparation of the U.S. inventory. However, the guidelines have not been accepted as a way to measure project benefits, making it difficult to stimulate voluntary market interest in N_2O emission reduction projects. For example, CCAR rejected an approach based on the IPCC methods for projects in California.

Construction of a transparent and credible performance-based accounting framework, with high quality projects that deliver real environmental benefits, is a complex task that requires technical and policy expertise. We believe that if a transparent and affordable accounting framework for quantifying N_2O emission reductions existed, markets would emerge from the private sector, local governments and the federal government.

2.0 PROPOSED STUDY APPROACH

The approach to the study is to investigate the potential for a methodology that can be implemented without a high level of expertise in modeling and without incurring the high costs of hiring experts or complex scientific equipment. Such a model must go beyond the application of broad-scale default factors that do not consider local conditions and thus can only poorly represent the reality of emissions from fertilizer use.

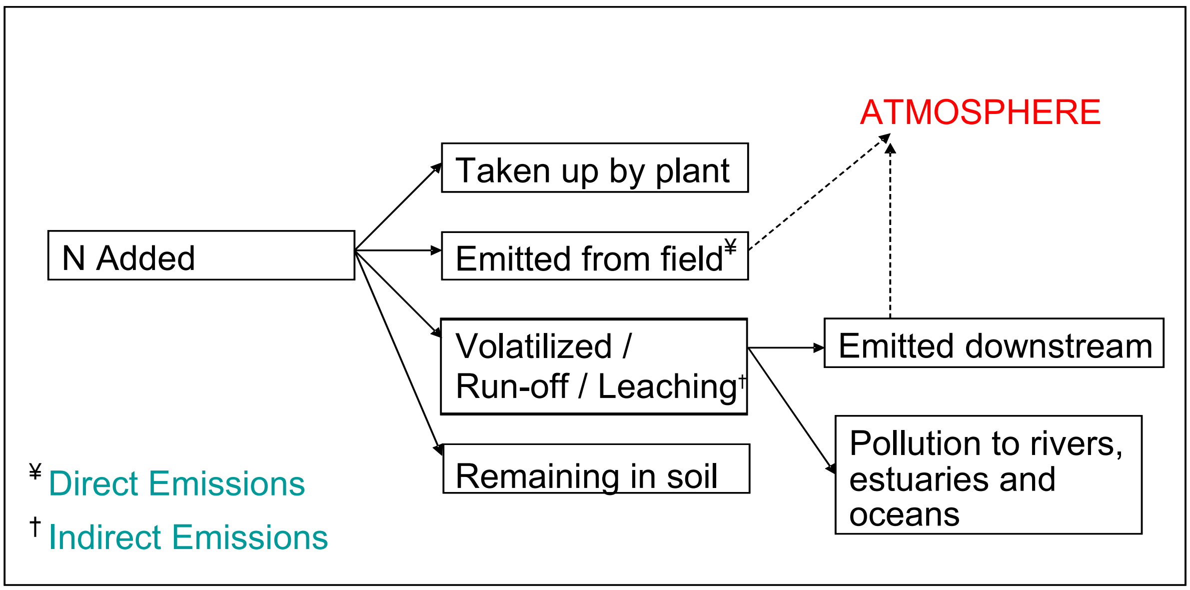
The study will test a proposed approach at three field sites across the US. The emissions as calculated by the simplified methodology will be compared to the emissions determined by a fully calibrated, process-based model.

The model used is DNDC (i.e. Denitrification-Decomposition), a computer simulation model for predicting crop yield, soil carbon sequestration, nitrogen leaching and trace gas emissions in agro-ecosystems. DNDC has been used worldwide for more than 17 years with more than 120 peer-reviewed publications on its use and its outputs.

A fully parameterized DNDC model includes 44 site-specific parameters (see Annex 1).

3.0 THEORETICAL BACKGROUND

As a gross simplification, the nitrogen added to fields as fertilizer can have four broad destinations. It can be taken up by the plant, it can remain in the soil as an enhanced concentration of N, it can be emitted directly from the field into the atmosphere as nitrous oxide or it can leach into the soil or run-off the top of the soil. The leached/runoff N can either continue downstream to cause pollution and/or it also can be emitted into the atmosphere as nitrous oxide.



The focus of our analyses is calculation of the quantity of nitrous oxide directly emitted to the atmosphere and the quantity indirectly emitted subsequent to run off/leaching or volatilization.

4.0 THE PROPOSED SIMPLIFIED APPROACH

4.1 Approach to Direct Emissions

A substantial literature exists detailing nitrous oxide emissions from farmland (see examples in Section 4.0). These studies are predominantly based on measurements taken in gas collection chambers placed out on fields. The results from these direct emission studies have been summarized and modeled in a series of papers by Bouwman and others (Bouwman et al. 2002a,b; Stehfest and Bouwman 2006). Bouwman et al (2002a,b) examined 846 N_2O emission measurements, and Stehfest and Bouwman (2006) added an additional 162 measurements in their study.

Both Bouwman et al. (2002b) and Stehfest and Bouwman (2006) created models estimating N_2O emissions from factors including:

- Fertilizer rate
- Fertilizer type
- Crop type
- Soil texture
- Soil organic carbon content
- Drainage
- Soil pH
- Climate

We at Winrock decided to chose the model of Bouwman et al. (2002b) as it has a longer list of variables that are likely to vary from site to site allowing more site-specific inputs into N_2O emission estimations. Specifically our chosen model varies from the more recent model of Stehfest and Bouwman (2006) in that it includes additional inputs related to measures of soil drainage and type of fertilizer, and it allows for the input of values of soil carbon content to vary over a wider range. The model of Stehfest and Bouwman allows greater differentiation based on climate (tropical, subtropical, temperate) but as this work is US-focused such variation adds little value to our efforts. The source data for the Stehfest and Bouwman model is richer but the paper itself states that “For N_2O there is only little reduction of the uncertainty due to the addition of new data”.

The Bouwman et al. (2002b) model is as follows:

$$Emission = e^{-0.4136 - \sum_{1}^{n\ 1} \text{Factor class (i)}}$$

Where:

Emission = Nitrous oxide emission (N_2O-N); kg/ha

Factors:

- N-rate * Fertilizer Type
- Crop Type
- Soil Texture
- Soil organic carbon content, %
- Soil drainage
- Soil pH
- Climate type
- Length of experiment
- Frequency of measurements

Factor/Factor Class	N[a]	Value
N_2O Model		
Constant		−0.4136
N-rate • Fertilizer Type Interaction[b]		
AA	38	0.0056
AF	59	0.0051
AN	117	0.0061
CAN	61	0.0037
NF	53	0.0034
Mix	25	0.0065
NP	16	0.0039
U	98	0.0051
AM	74	0.0021
AMF	41	0.0042
Crop type		
Grass	177	−1.268
Grass-clover	16	−1.242
Leguminous crops	36	−0.023
Other upland crops	512	0
Wetland rice	61	−2.536
Soil texture		
Coarse	447	−0.008
Medium	147	−0.472
Fine	134	0
Soil organic carbon, content, %		
$SOC \leq 1.0$	92	0
$1.0 < SOC \leq 3.0$	353	0.140
$3.0 < SOC \leq 6.0$	126	0.580
$SOC > 6$	18	1.045
Soil drainage		
Poor	193	0
Good	460	−0.420
Soil pH		
$pH \leq 5.5$	93	0.000
$5.5 < pH \leq 7.3$	359	0.109
$pH > 7.3$	109	−0.352
Climate type[c]		
TE	650	0
STR	196	0.824
Length of experiment, days		
<120	343	0
120–180	132	0.004
180–240	42	0.487
240–300	34	0.657
>300	277	0.825
Frequency of measurements[d]		
>1 meas/day	140	0
1 meas/day	286	0.125
1 meas/2–3 day	78	1.639
1 meas/3–7 day	262	0.825
<1 meas/week	46	0.788

4.2 Approach to Indirect Emissions

Run-off / Leaching

Between 10 and 80% of the nitrogen added to soils is typically lost through runoff/leaching (IPCC 2006). A proportion of this nitrogen is converted to nitrous oxide through the processes of nitrification and denitrification. This indirect emission is one of the most poorly defined N_2O sources (Nevison 1999).

Under the procedure proposed by the IPCC, the added nitrogen is multiplied by FRACLEACH, which is the proportion of added N that is leached/runoff from agricultural fields. This value is set at 0.30 but a range of 0.1 to 0.8 is given. The N_2O emission (EF_5) from this leached/runoff proportion is set at 0.0075 with a range of 0.0005 and 0.025.

The literature provides no simple models or relationships that predict either FRACLEACH or EF_5 (e.g. Reay et al. 2003; Sawamoto et al. 2005). We therefore propose to use the following approach:

FRACLEACH

Various studies have shown that the IPCC default for FRACLEACH of 0.3 is too high in developing country contexts (e.g. Brown et al. 2001 in the UK; Stephen et al. 2005 in New Zealand). However, the precise value is scenario-specific with higher values of FRACLEACH appropriate for particular combinations of sites and crops in each of the countries studied. Nevison (1999) wrote a background paper to the IPCC specifically on indirect nitrous oxide emissions. Nevison showed that the following factors influence the proportional leaching:

- Drainage tiles increase leaching to rivers (and was the default in most of the studies Nevison examined)
- No-Till systems decrease leaching
- Deep-rooted crops decrease leaching loss

However, the most significant factor determining interannual variability in leaching is precipitation. Low leaching occurs in dry years followed by large leaching losses in a subsequent wet year.

Our approach in this study is to use site-specific factors to determine how large leaching/runoff is liable to be.

We here suggest the following approach which builds from the findings of Nevison but necessarily makes assumptions on the scale to which each of the factors impacts the quantity of leaching. The assumption is made that under the standard conditions from which the default data were derived, the IPCC value of 0.3 would be used. Therefore where drainage tiles are present together with tillage and shallow-rooted crops and where rainfall exceed potential evapotranspiration and does not significant depart from mean annual rainfall in either the year of assessment or the previous year then the IPCC default of 0.3 will apply. The findings do require many assumptions and as such the results will be tested against an empirical model. The approach is (but keeping in mind these assumptions will be tested further against other models/data):

Where annual rainfall is less than potential evapotranspiration then:

FRACLEACH = 0.05 (IPCC 2006)

Otherwise:

$$FRACLEACH = PRF * RF * F$$

Where:

F	= Leaching factor based on presence or absence of tile drainage, tillage and deep-rooted crops
RF	= Leaching factor based on precipitation in current year of N_2O emission assessment
PRF	= Leaching factor based on precipitation in year prior to current N_2O emission assessment

F =

If	+ Tile	+ Till	- Deep-Rooted		=	0.30
If	- Tile	+ Till	- Deep-Rooted	or		
	+ Tile	- Till	- Deep-Rooted	or		
	+ Tile	+ Till	+ Deep-Rooted		=	0.20
If	- Tile	- Till	- Deep-Rooted	or		
	- Tile	+ Till	+ Deep-Rooted	or		
	+ Tile	- Till	+ Deep-Rooted		=	0.15
If	- Tile	- Till	+ Deep-Rooted		=	0.125

Where:

Tile	= presence (+) or absence (-) of tile drainage
Till	= presence (+) or absence (-) of tillage as part of agricultural practices
Deep-rooted	= presence (+) or absence (-) of deep-rooted crop in assessment year

$$RF - \frac{AR}{MAR}$$

Where:

AR	= Annual rainfall; inches
MAR	= Mean annual rainfall; inches

Rainfall may be as recorded at nearest meteorological station.

PRF =

If previous year's rainfall = < ½ MAR and AR > MAR	=	2
otherwise	=	1

Where:

AR = Annual rainfall; inches

MAR = Mean annual rainfall; inches

Rainfall may be as recorded at nearest meteorological station.

EF_5

For EF_5 there is no literature to support any site-specific factors that would influence where in the IPCC range the emission proportion would lie (between 0.0005 to 0.025). We therefore propose here to use the suggested IPCC value of 0.0075 in the methodology.

Volatilization

Further indirect emissions arise through volatilization as NH_3 or NO_x followed by deposition nitrification / denitrification and emission as N_2O. The IPCC uses $Frac_{GASF}$ as the proportion of fertilizer that is volatilized and EF4 as the emission factor for this volatilized proportion subsequent to deposition. The IPCC has set $Frac_{GASF}$ to be equal to 0.1 (range 0.03 – 0.3) and EF_4 to be equal to 0.01 (range 0.002 – 0.05). Note that leaching and run-off account for 75% of indirect emissions with atmospheric deposition only a fifth of the magnitude of emissions due to leaching (Nevison 1999). Studies on this form of indirect emission are very limited and are largely focused on forest soils. We thus here use the IPCC method to estimate indirect emissions from the volatilization pathway.

5.0 THE DNDC MODEL

During the past decade, a number of agro-ecosystem models were developed that incorporate the complex interactions among climate, soil, plant growth and management practices. The modeling efforts have provided opportunities to assess the best management practice strategies in a range of scales from individual farms to watersheds and regions (Tsuji et al., 1994; Ahuja et al. 2000; Zhang et al., 2002; Donner and Kucharik, 2003; Li et al., 2006). Among these modeling efforts, the process-based, biogeochemical model, Denitrification-Decomposition or DNDC, was developed originally for estimating greenhouse gas emissions from U.S. agricultural lands (Li et al., 1992).

DNDC is a unique soil biogeochemical model because it simulates both aerobic and anaerobic soil conditions, estimates crop yields based on a detailed crop physiology-phenology model, and is designed for assessing the net impact of alternative management (mitigation strategies) on long-term soil organic carbon (SOC) dynamics and emissions of N_2O, NO, CH_4, and NH_3 from both upland and wetland agricultural ecosystems. The model has been used to estimate C sequestration, nitrate leaching, and emissions of N_2O, NO, CH_4 and NH_3 in agricultural lands in the U.S. and Worldwide. DNDC model results have been independently tested and validated by many researchers worldwide and now is utilized for national trace gas inventory studies in the U.S., Canada, the U.K., Germany, Italy, Belgium, New Zealand, China, Japan, Thailand and the Philippines.

The core of DNDC is a soil-biogeochemisty model which has been linked to vegetation models to simulate soil organic carbon (SOC) dynamics, nitrate leaching dynamics, emissions of nitrogen gases (N2) and several trace gases including N_2O, NO, NH_3 and CH_4 from agricultural ecosystems. DNDC consists of the six sub-models for soil climate, crop growth, decomposition, nitrification, denitrification, and fermentation. The six interacting sub-models include the fundamental factors and reactions, which integrate carbon and nitrogen cycles into a computing system (Li et al. 1992, Li 2000, Zhang et al. 2001). DNDC is unique it is approach for modeling bulk soil redox dynamics and response of microbial communities and reaction rates based on soil redox and environmental controls. Here we describe the model fundamentals of the soil moisture and nitrogen dynamics.

5.1 Modeling Soil Moisture Dynamics

DNDC simulates soil moisture dynamics by mainly tracking water movement in vertical dimension in soil profile from the surface to a depth of 0.5 m (Figure 1). DNDC has a one-dimensional soil water flow to calculate average hourly and daily soil moisture profile. The default thickness of modeled soil profile is 50 cm. DNDC characterizes soil physical properties by soil texture, following the work of Clapp and Hornberger (1978). The soil profile is divided into a series of horizontal layers. Typical vertical spatial resolution is 2 cm and time step is an hour. Each layer is assumed to have uniform texture and moisture. For each time step, water flow between layers is determined by the gradients of soil water potential (Ritchie et al., 1988). During a simulated rainfall event, rainwater is added on the surface of the soil then infiltrates into the soil profile layer by layer to fill the soil pore. Gravity drainage occurs when the soil moisture is higher than the field capacity in a layer. Water efflux from the bottom of the modeled profile is driven by gravity drainage only (Van Bavel et al., 1978). If the rainfall intensity, which is fixed as 0.5 cm/hr in DNDC, and irrigation is higher than the soil saturated hydraulic conductivity, ponding water will form on the soil surface and a surface runoff flow will be calculated based on the defined soil slope. Water withdrawal from the soil profile is calculated based on transpiration and evaporation. Potential evapotranspiration (ET) is calculated as daily average values using the Thornthwaite formula, in which potential ET is determined by mean air temperature and then adjusted for daylight length relative to 12 hours (Dunne and Leopold, 1978). Potential ET is separated into potential transpiration and evaporation. Daily potential transpiration is determined by daily water demand by plants, which is quantified based on the modeled daily increment of crop biomass. Actual plant transpiration is jointly determined by potential transpiration and soil water content. Potential evaporation is the difference of potential ET and actual transpiration. Evaporation is allowed to occur only for the top 20 cm of soil profile. By tracking precipitation, plant interception, ponding water, surface runoff, infiltration, gravity drainage, transpiration, and evaporation, DNDC simulates water movement in the vertical dimension of soil profiles. Detailed descriptions of the hydrological equations and parameters have been reported in several former publications (e.g., Li et al., 1992; Zhang et al., 2002 a,b).

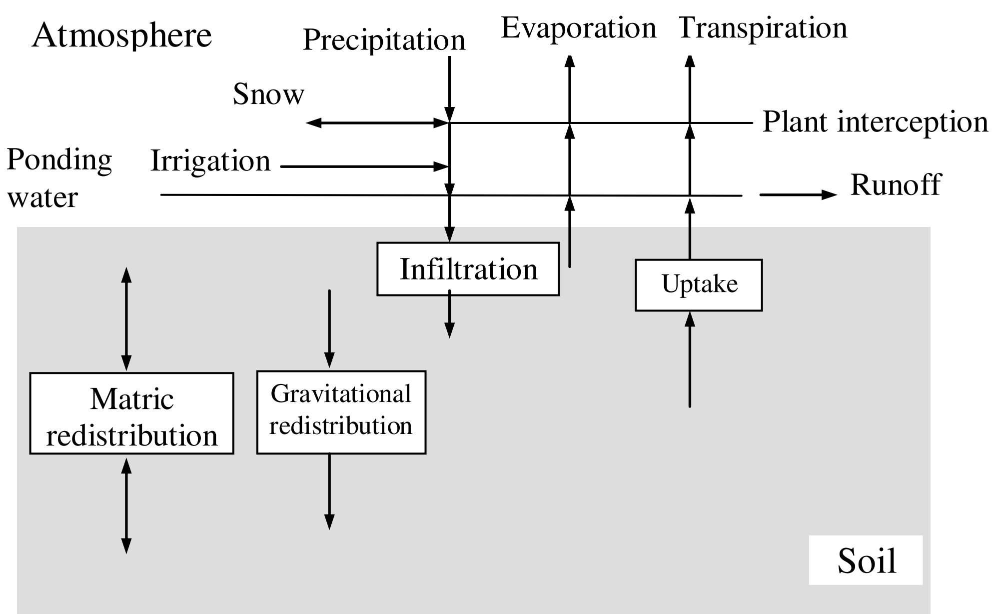


Figure 1 DNDC tracks soil moisture dynamics by primarily simulating vertical water movement in top 0.5 meters of the soil profile.

5.2 Modeling Nitrogen Dynamics

DNDC models soil N dynamics by precisely tracking several biogeochemical processes involving nitrogen, namely decomposition, ammonification, ammonium-ammonia equilibrium, microbial assimilation, plant uptake, ammonia volatilization, nitrification, and denitrification (Li et al., 1992; Li 2000). In DNDC, when fresh litter is incorporated in the soils, it will be partitioned into the soil organic matter pools, which possess different quality (i.e., C/N ratio) and hence different specific decomposition rates. Litter will be first assimilated into soil microbial biomass. During the assimilation, the microbes demand free NH_4^+ or NO_3^- ions from the soil environment due to the difference in C/N ratio between the microbes and litter. After death of the microbes, they will turn into humus. Active humus can further transfer to passive humus through the microbial activity. During the decomposing processes, a part of organic N is redistributed into the soil organic pools, and other part is turned into NH_4^+ through ammonification. The free NH_4^+ ions dissolved in the soil liquid phase can be absorbed by the plant roots, adsorbed by clay, or oxidized to NO_3^- by the nitrifiers. The schematic in Figure 2 is a generalization of N pools and fluxes simulated by DNDC.

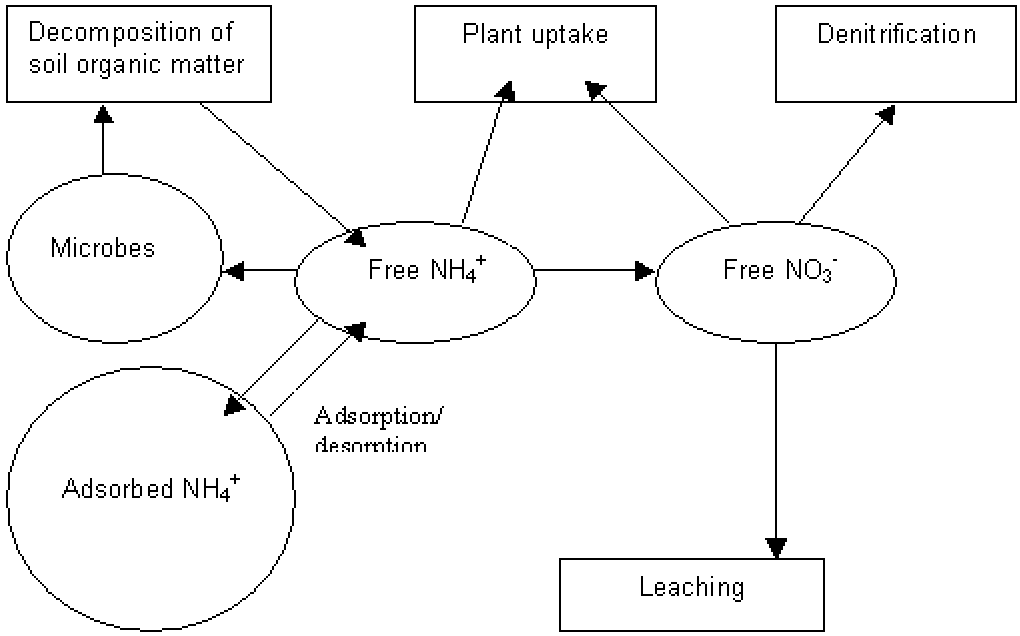


Figure 2. Major nitrogen pools and fluxes simulated in DNDC

In DNDC, management practices affect N leaching, soil carbon dynamics and N2O emissions by altering soil water fluxes, nitrogen cycling and nitrate content. Examples are fertilizer application which directly adds N compounds into the soil or irrigation which effects moisture content, water transport and N movement in the soil.

5.3 DNDC input parameters and output results

Soil characteristics were obtained from field measurements. In addition, we examined variability of these conditions across each state using the Natural Resources Conservation Service (NRCS) SSURGO (1:18,000) databases. SSURGO provides detailed information that was designed for analyses at the landowner, farm, or county level. SSURGO data is now available for most of the US. DNDC requires at a minimum four soil properties: soil bulk density, clay fraction, pH, and organic carbon content. The minimum and maximum values of these properties are provided in the SSURGO databases and are used to assess sensitivity of model simulations to expected variability in soil conditions.

Climate inputs to DNDC include daily values of minimum and maximum air temperature, precipitation, and solar radiation. Climate data were obtained from three sources: a) the National Climate Data Center (NCDC), b) California Irrigation Management Information Service (CIMIS) or c) the DAYMET. NCDC historical climate archives can be obtained for hundreds of weather stations throughout the Midwest, and a nearest neighbor approach can be used to apply this weather station point-data to any location in the area of analysis. Alternatively, DAYMET is a model that generates daily surfaces of temperature, precipitation, humidity, and radiation over large regions of complex terrain (Thornton and Running 1999). Using weather station and elevation parameters as input, DAYMET has generated a 24-year (1980-2003) daily climate data set at 1 km resolution. In order to simulate nutrient cycling for these specific fields, DNDC requires a set of input information about climate and site characteristics. Climate information consists of daily maximum and minimum temperatures and daily rainfall.

6.0 FIELD MEASUREMENTS

Field data collection serves the purpose of providing the inputs to the methods proposed above. In addition, additional data were collected to inform the DNDC model run by Applied Geosolutions to simultaneously calculate likely N_2O emission to provide a basis for comparison.

It was decided that three different crops would be examined in three disparate parts of the country. The stipulation was included that the crop had to significant in the region and had to be fertilized with nitrogenous fertilizer under business as usual practice.

The three sites (Figure 1) were:

Region	***State***	***Crop***
South	Arkansas	Cotton
Mid-West	Iowa	Corn/Maize
West Coast	California	Lettuce

Farms were selected based on contacts available to Winrock and farmer willingness.

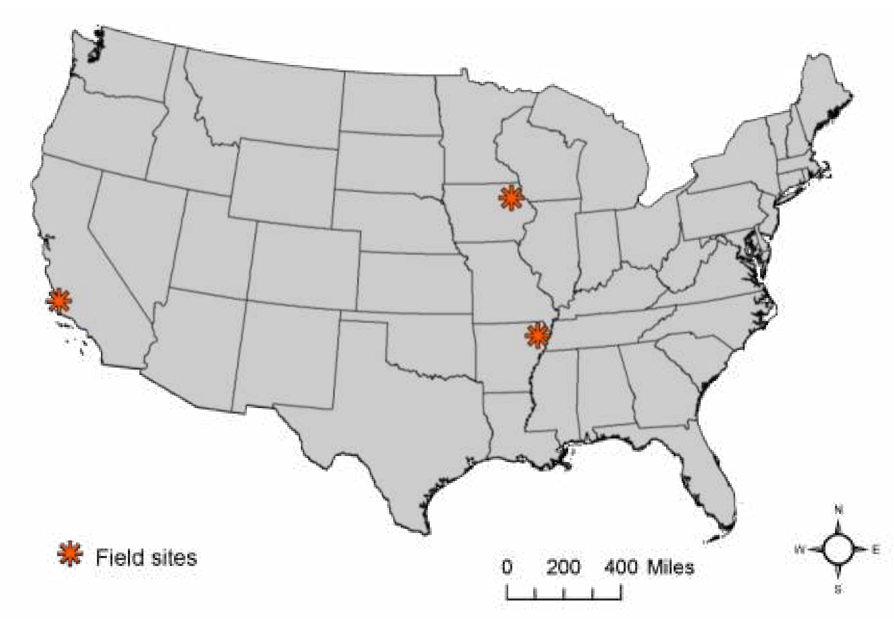


Figure 3. Location of the three field test sites

At all three sites the crops received inorganic fertilizers. The fertilizers were applied at different rates and stages of crop development. The application rates depended on the soil test and crop requirement.

6.1 The Field Sites

After initial discussions with the farmers and area extension agents, the three sites in Arkansas, Iowa and California were visited in April (Arkansas and Iowa) and June 2009 (California) for discussions with the farmer and initial data collection that also included soil sampling

In each case farmers were given a questionnaire to provide answers about their farm and their practices (Annex 2). Weather data were collected from the closest available weather stations.

6.1.1 Arkansas

The farm in Arkansas is located in Craighead County. The focus of the study is on 81.5 acres of fields growing cotton (but in an alternate year cotton/soybean rotation). At the site temperatures vary from an average January low below freezing to average July and August highs of over 90 ^{o}F. Mean annual precipitation is 46 inches with rainfall peaks on April and November but no month with less than 2.7 inches on average (Figure 2).

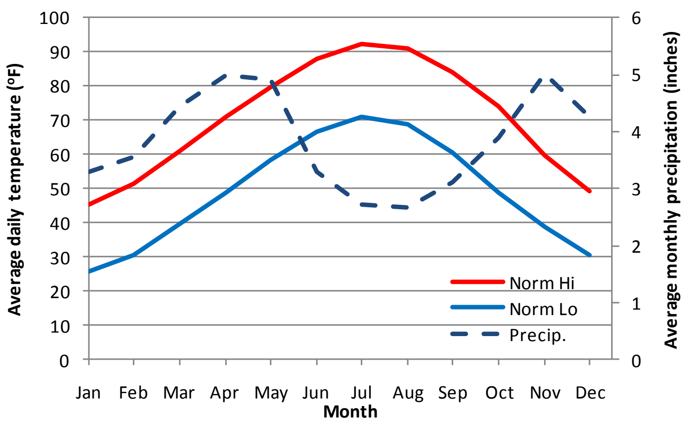


Figure 4. Mean high and low temperatures in each month and mean monthly precipitation totals for the study site in Arkansas

The fields had a slope of less than 1%. Planting was in May 2009 and harvest in November 2009. Harvest was delayed due to high rainfall. Annually the fields are tilled 6 times, fertilizer is applied once after planting and irrigation occurs 5 to 8 times. Details given in Table 1 in section 7.0.

Figure 5. The cotton fields in Arkansas at the time of harvest

6.1.2 Iowa

The farm in Iowa is located in Fayette County. The focal fields are 74.1 acres of corn / maize. At the site low temperatures vary from below freezing temperatures between November and March, to summer (June-August) average highs of over 80 ^{o}F. Mean annual precipitation is 32 inches with summer peak of over 4.25 inches per month in July and August to winter month low rainfall amounts of approximately 1 inch/month on average (Figure 3).

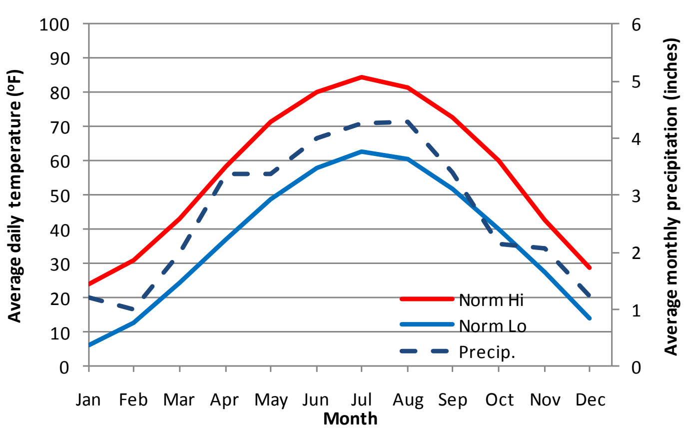


Figure 6. Mean high and low temperatures in each month and mean monthly precipitation totals for the study site in Iowa

The fields had a slope of between 2 and 5%. Planting was in May 2009 and harvest in November 2009. Harvest was delayed due to high rainfall. Annually the fields are tilled 3 times, fertilizer is applied twice and no irrigation. Details given in Table 1 in section 7.0.

6.1.3 California

The farm in California is located in San Luis Obispo County. The farm grows horticultural crops with the focal fields being 9.9 acres of iceberg lettuce. Because of limited rainfall in the region, horticultural crops are primarily produced under irrigation with multiple cropping seasons within a year. The site is characterized by cool temperate conditions with average highs varying only between 65 and 73 ^oF over the year and average lows of between 42 and 53 ^oF. Mean annual precipitation is 18 inches with winter peak of between 3 and 4 inches per month between January and March and a summer drought with an average of less than 1/20 inch of rain in July and August combined and less than an inch of rain on average between the beginning of May and the end of September (Figure 4).

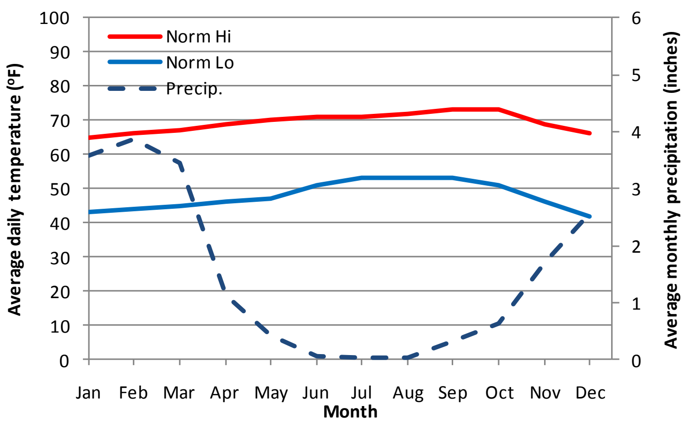


Figure 7. Mean high and low temperatures in each month and mean monthly precipitation totals for the study site in California

The fields had a slope of 2%. Planting was in June 2009 and harvest in August 2009. Annually the fields are tilled 3 to 4 times; fertilizer is applied continuously before planting, through drip irrigation and side dressing. Details given in Table 1 in section 7.0.

6.2 Field data collection

6.2.1 Methods for soil sampling and analysis

To assess likely emissions resulting from fertilizer use soil samples were collected both before and immediately after harvest. Soil samples were taken from a depth of 15 cm by use of soil probe for soil carbon (SC), soil nitrogen (SN), soil texture and bulk density samples. For each sample unit, a pH reading was taken as well as two soil samples: one for soil carbon, soil nitrogen and texture, and another for soil bulk density (BD). After assessment of the farmers' soil sampling documents and visual observation of the field, the sample units were distributed randomly within the fields. Within each sampling unit 6-8 sub-soil samples were randomly taken from different locations and mixed into one composite sample for soil C analysis. One bulk density sample was taken from the center of every sample unit. Soil bulk density was calculated as the oven-dried mass divided by the volume of the probe. In all cases, parts of the land that seemed to be eroded, dead furrows and fence lines were not sampled. The collected samples were shipped to the laboratory for analysis of bulk density, total soil carbon and inorganic soil nitrogen (SN = nitrate -N + NH_4-N) and textural analysis.

Soil carbon and nitrogen stocks were estimated to a depth of 15 cm using the total SC (%), SN (mg/kg), and bulk density data (g/cc). The amount of soil C present on a per hectare (ha) basis was determined, as follows:

Soil carbon stocks (t/ha) = BD (g/cc) x 1.5 x SC (%) x 10

Where BD is the bulk density of the soil; SC is the total soil carbon value (%).

The same approach was used for nitrogen pools

6.2.2 Other data collected

The farmers were asked to record the date of each fertilization event and the quantity and type of fertilizer applied. Farmers also recorded incidences of tillage and irrigation. Upon harvest the yields were also disclosed. The Winrock team collected crop samples for nitrogen content. Samples were collected at each of the sites randomly from across the sampling fields.

7.0 RESULTS

7.1 Questionnaire and pre-planting collected data

Results for soil sampling pre-planting and the data derived from the questionnaire are summarized in Table 1.

Table 1. Data collected from questionnaires and sampling pre-planting

		State	
Parameter	**Iowa**	**Arkansas**	**California**
Soil Data			
Bulk density (g/cm^3)	1.2	1.5	1.0
Sand (%)	36	54	66
Silt (%)	38	36	21
Clay (%)	26	10	13
pH (in water)	6.6	6.2	7.0
SOC (%)	2.6	0.70	0.84
Slope (%)	2 - 5	0.75	2
NO_3 (mg N/kg)	11.4	10.4	68
NH_4^+ (mg N/kg)	1.9	1.4	1.6
Crop Data			
Crop Type	Corn	Soybean / Cotton Rotation	Horticultural Crops (Iceberg Lettuce)
Planting date	May	May	June
Harvest data	November	November	August
Is the crop a cover crop	No	No	No
Maximum grain production (t/ha)	13.3	Cotton=3.97	6.8 (fresh produce heads)
Tillage Data			
How many applications in this year	3 (on one crop): fall plough, level, seed bed preparation	6: Disk, landplane, hipper, bed knocker, planting	3-4 depending on crop type
Date of tillage	May	May	02-Jun-09
Tillage method (depth for each tillage)	15-25 cm	15-25 cm	15-25 cm, Disking used to make beds
Fertilizer			
How many fertilizer applications each	2	1	3

year			
Month of fertilizer application, Application method, Amount applied (N kg/ha), Type of fertilizer	1. Preplant, 2. 6" Corn plant	Applied after planting	1. Before planting 2. Side dress 3. In Drip
Amount applied (kg N/ha)	1. 18 kg N/ha 2. 7 kg N/ha	17.6 kg N/ha (300 lb/ac)	1. 8.3 kg N/ha 2. 20 kg N/ha 3. 7.4 kg N/ha
Type of Fertilizer	UAN	32% N	Before (15-5-30) / UAN side dress / CAN in drip
Use of controlled released fertilizer	No	Yes (10-14 days)	No
Are nitrification inhibitors used?	No	No	No
Irrigation Data			
How many irrigation events in a year	None	5 to 8	10 (per crop season)
Date of each irrigation event	None	June - August	
Irrigation type (sprinkler, furrow, drip tape)	None	Furrow	Sprinkler * 5 events Drip * 5 events
Amount for each event	None	1.5 “	Sprinkler 43,200 gal/ac Drip 40,000 gal/ac
Irrigation water pH	None	6.5	7.1
Irrigation water N content	None	Not measured	207.9 lb/ac.ft (7.7 ha cm)
Tile drainage	Yes	None	None

Bulk density ranged between 1 and 1.5 g/cc for the sampled fields. Iowa had the highest soil carbon, soil carbon in Arkansas and California were similar to each other.

7.2 Recorded weather data

Rainfall data recorded at weather stations close to the field sites (Table 2 and Figure 8) demonstrate the exceptionally wet year in Arkansas and the dry conditions in California.

Table 2. Rainfall data (in inches) recorded for the three field data sites

Month	Arkansas	Iowa	California
January	2.74	0.52	0.71
February	4.67	0.62	4.68
March	4.45	3.03	0.69
April	7.87	6.03	0.1
May	8.25	2.69	0.08
June	6.45	2.45	0
July	6.87	5.94	0
August	4.17	4.80	0.01
September	7.98	2.44	0.01
October	11.71	5.66	1.44
November	0.97	0.66	0
December	9.72	2.17	4.37
2009 Total	75.85	37.01	12.09
2008 Total	46.08	49.45	10.58
Long Term Average	46.18	32.34	17.79

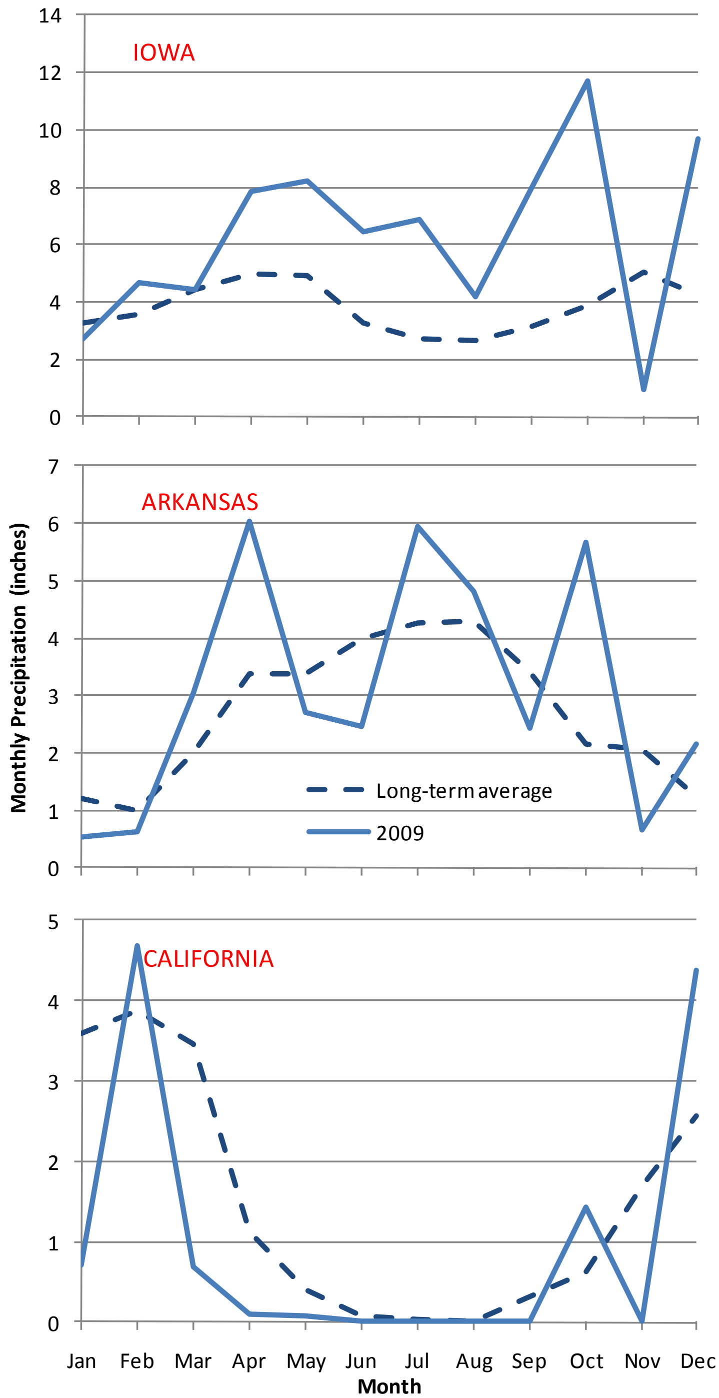


Figure 8. Rainfall at the three sites in 2009 relative to the long-term average

7.3 Actual fertilizer use and irrigation

In Table 3 the actual fertilizer used and irrigation applied is detailed.

Table 3. Actual fertilizer and irrigation across the three sites

	Arkansas	Iowa	California
Type of Fertilizer	UAN	UAN	15-5-30, UAN, CAN
Amount Applied (lbsN/ac)	185	95.5	196
Timing (lbsN/ac)	Pre: 135 V4: 55	After planting	Pre: 45 (15-5-30) Side: 111 (UAN) Drip: 40 (CAN)
P and K	Yes	Yes	Yes
Irrigation	No	Yes	Yes
Amount (gal/ac)	-	67,842	284,336
Timing (gal/ac)	-	3 events	Pre: 40,728 Sprinkler: 108,608 (7 events) Drip: 135,000

7.4 Post-harvest data

7.4.1 Iowa

Soil data

Table 4. Soil data from the pilot site in Iowa (corn); the mean +/- 95% confidence interval are reported.

SOIL DATA	Before Planting		After Harvest	
NO_3 (mg N/kg)	11.6	± 1.1	5.5	± 1.0
NH_4^+ (mg N/kg)	2.0	± 0.2	3.4	± 0.8
Sum of N (mg N/kg)	13.7	± 1.2	8.9	± 1.6
Bulk density (g/cm^3)	1.30	± 0.07	1.39	± 0.03
% Carbon	2.39	± 0.30	2.90	± 0.28

Yield:

Harvested quantity was 211 dry bushels/acre (2.1 t C/acre).

Not harvested:

Pre-harvest stock:

Grain	2.2 t C/ac (± 0.3)
Stover and Core	1.2 t C/ac (± 0.4)
Roots	0.4 t C/ac (± 0.1)

Therefore the stock left in the field was equal to:

1.7 t C/acre

7.4.2 Arkansas

Soil data

Table 5. Soil data from the pilot site in Arkansas (cotton); the mean +/- 95% confidence interval are reported.

SOIL DATA	Before Planting		After Harvest	
NO_3 (mg N/kg)	10.4	± 1.1	2.2	± 0.2
NH_4^+ (mg N/kg)	1.4	± 0.2	2.4	± 0.3
Sum of N (mg N/kg)	11.9	± 1.2	4.6	± 0.4
Bulk density (g/cm^3)	1.50	± 0.07	1.60	± 0.03
% Carbon	0.67	± 0.03	0.69	± 0.05

Yield:

The quantity harvested 1.55 bales/acre or 763 lbs/acre

Not harvested:

Pre-harvest stock:

Lint	0.5 t C/ac (± 0.1)
Stem	1.7 t C/ac (± 0.4)
Roots	0.2 t C/ac (± 0.02)

The stock left in the field was equal to:

1.9 t C/acre

7.4.3 California

Soil data

Table 6. Soil data from the pilot site in California (iceberg lettuce); the mean +/- 95% confidence interval are reported.

SOIL DATA	Before Planting		After Harvest	
NO_3 (mg N/kg)	75.1	± 8.6	90.6	± 11.1
NH_4^+ (mg N/kg)	1.5	± 0.2	1.4	± 0.3
Sum of N (mg N/kg)	82.4	± 8.3	92.1	± 11.2
Bulk density (g/cm^3)	0.96	± 0.08	0.99	± 0.02
% Carbon	0.84	± 0.03	0.72	± 0.05

Yield:

The quantity harvested was 700 cartons / acre or 35,000 lbs / acre

Not harvested:

- 15,000 lbs / acre of unharvested lettuce
- Roots
- 3,500 lbs / acre Wrapper leaves

7.4.4 Across sites

Table 7. Direct comparison in soil results before and after harvesting across the three pilot sites

Parameter	STATE					
	Iowa		Arkansas		California	
SOIL DATA	Before Planting	After Harvest	Before Planting	After Harvest	Before Planting	After Harvest
NO_3 (mg N/kg)	11.6	5.5	10.4	2.2	75.1	90.6
NH_4^+ (mg N/kg)	2.0	3.4	1.4	2.4	1.5	1.4
Sum of N (mg N/kg)	13.7	8.9	11.9	4.6	82.4	92.1
Bulk density (g/cm^3)	1.30	1.4	1.50	1.6	0.96	0.99
% Carbon	2.39	2.9	0.67	0.7	0.84	0.72

Table 8. N-content of tissue samples at time of harvest

	Arkansas	Iowa	California
NH_4-N (ppm)	158	<100	900
NO_3-N (ppm)	150	7.66	2,622
Nitrogen (%)	1.8	1.02	3.8
C:N ratio	40	44	12

8.0 CALCULATED EMISSIONS

8.1 Proposed methodology

8.1.1 Direct Emissions

The direct emissions from the sites in Arkansas, Iowa and California were estimated using the proposed simplified methodology (see Section 4.1). The factors and final estimations are given in Table 9.

The high fertilizer applied paired with the higher soil carbon percentages and the exclusive use of urea ammonium nitrate fertilizer led to the estimated emission being highest in Iowa.

Table 9. Factors for and calculation of direct nitrous oxide emissions from pilot farm sites using the proposed simplified methodology

	Arkansas	Iowa	California
N Rate (kg N/ha) * Fert	107 * UAN	207 * UAN	50.4 * Mix 124 * UAN 45 * CAN
Crop Type	Other Upland Crop	Other Upland Crop	Other Upland Crop
Soil Texture	Sandy Loam (Medium)	Loam (Medium)	Sandy Loam (Medium)
Soil Organic Carbon %	≤ 1%	1 - 3% and 3 - 6%	≤ 1%
Soil Drainage	Good	Good	Good
Soil pH	5.5 < pH ≤7.3	5.5 < pH ≤7.3	5.5 < pH ≤7.3
Climate Type	Temperate	Temperate	Temperate
Length of Experiment	120-180 days	120-180 days	< 120 days
Frequency of Measurements	< 1 measurement/week	< 1 measurement/week	< 1 measurement/week
EMISSION kg N_2O/ha	1.85	4.22	3.28
EMISSION kg CO_2-e/ha	551	1258	977

Total emissions of $CO_{2\text{-e}}$ is about 0.5 to 1.3 t/ha over the growing season.

8.1.2 Indirect Emissions

The indirect emissions due to run-off / leaching from the sites in Arkansas, Iowa and California were estimated using the proposed simplified methodology (see Section 4.2). The factors and final estimations are given in Table 10.

As with direct emissions, the indirect runoff / leaching emissions are highest in Iowa. The lowest emissions are in California principally due to the low rainfall in the study year relative to mean rainfall for the area.

Table 10. Factors for and calculation of indirect nitrous oxide emissions through run-off / leaching from pilot farm sites using the proposed simplified methodology

	Arkansas	Iowa	California
N applied (kg N/ha)	107	207	220
2008 Rainfall (inches)	46.1	46.1	10.6
2009 Rainfall (inches)	75.9	37.0	12.1
Mean Annual Rainfall (inches)	46.2	32.3	17.8
PRF	1	1	1
F	0.15	0.2	0.2
RF	1.644	1.150	0.680
FRACLEACH	0.25	0.23	0.14
N-Leached (kg N/ha)	26.4	47.5	29.9
EF5	0.0075	0.0075	0.0075
EMISSION kg N_2O/ha	0.31	0.56	0.35
EMISSION kg CO_2-e/ha	93	167	105

F = Leaching factor based on presence or absence of tile drainage, tillage and deep-rooted crops

RF = Leaching factor based on precipitation in current year of N2O emission assessment

PRF = Leaching factor based on precipitation in year prior to current N2O emission assessment

Global Warming Potential used for N2O is 298 (to convert from N2O to CO2 equivalent

The indirect emissions caused by volatilization and atmospheric deposition are given in Table 11. As they follow the IPCC method they are proportional to the N applied.

Table 11. Factors for and calculation of indirect nitrous oxide emissions through volatilization / deposition from pilot farm sites

	Arkansas	Iowa	California
N applied (kg N/ha)	107	207	220
FRACGASF	0.1	0.1	0.1
EF4	0.01	0.01	0.01
EMISSION kg N_2O/ha	0.17	0.33	0.35
EMISSION kg CO_2-e/ha	50	97	103

The total indirect emissions are given in Table 12. Indirect emissions are highest in Iowa (0.29 t CO_2-e/ha) driven by the high emissions due to run-off/leaching.

Table 12. Total indirect emissions as calculated from pilot farm sites using simplified methodology

	Arkansas	Iowa	California
Leaching / Runoff t CO_2-e/ha	0.09	0.20	0.11
Volatilization t CO_2-e/ha	0.05	0.10	0.10
Total Indirect t CO_2-e/ha	0.14	0.29	0.21

8.1.3 Total Emissions

The total emissions as estimated using the proposed simplified methodology combining direct and indirect emissions are given in Table 13. Per hectare emissions range from 0.72 tons of carbon dioxide equivalent per hectare (0.29 t CO_2-e/acre) in Arkansas to 1.55 t CO_2-e/ha (0.63 t CO_2-e/ac) in Iowa.

Table 13. Calculated direct and indirect emissions from the pilot farm sites using the proposed simplified methodology

	Arkansas	Iowa	California
Direct Emission kg CO_2-e/ha	551	1258	917
Indirect Emission kg CO_2-e/ha	143	292	208
Total Emission t CO_2-e/ha	0.69	1.55	1.13

8.2 DNDC modeling

For this study, we processed climate data from CIMIS and NCDC climate stations for 2009. Soil information includes soil texture, pH, bulk density, carbon and nitrogen contents and hydrological characteristics. These soil data were collected for each of the sites. Table 13 presents the soil parameters, climate station and atmospheric nitrogen deposition (derived from NADP) for each site.

Table 13. Crop management practices

Model Input Parameters	Iowa Corn	Arkansas Cotton	California Lettuce
Latitude:	42.74	35.791	35.09
NO_3NH_4 in Rainfall (ppm)	4.96	4.55	0.65
NO_3_of_Atmosphere	0.06	0.06	0.06
BaseCO_2_of_Atmosphere	350	350	350
Climate Station – 2009 data	Tripoli	Paragould	Nipomo
Soil_data:			
Bulk Density	1.2	1.5	0.96
Soil_pH	6.8	6.1	7
SOC (% at surface)	0.029	0.007	0.0072
Clay_fraction	0.26	0.1	0.13
Field_capacity	0.52	0.32	0.4
Wilting_point	0.24	0.15	0.2
Hydro_conductivity	0.02268	0.1248	0.02592
Soil_porosity	0.421	0.435	0.485

8.2.1 DNDC Calibration and Testing

Soil Mineral N: DNDC starts simulations always at the beginning of the calendar year with a series of boundary conditions or internal parameters (e.g., initial $NO3^-$ and NH4+ contents, soil organic carbon partitioning etc.) and may produce $NO3^-$ and NH4+ profiles differing from the observed $NO3^-$ and NH4+ profiles for a specific day. However, since we do not have information on prior years cultivation practices, we have to estimate the initial soil mineral N pools at the start of the simulation. The initialization of soil $NO3^-$ and NH4+ pools at the beginning of the year were set so that the model concentration were close to the observed concentration from the pre-plant soils test. However, for the Iowa corn simulation due to several dramatic strong freeze/thaw events in March 2009, most of the soil mineral N was lost due to high nitrification and denitrification rates. We tested this against other climate years and found this to be somewhat unique to 2009. However, since the field data were collected in 2009, we decided to use the 2009 climate data for all the corn scenarios. Thus, for the corn site runs, we did not have reasonable initialization resulting in a modeled versus observed discrepancy of 4-5 kg $NO3^-$ per hectare at pre-plant.

Crop Growth: DNDC uses an ecophysiological process growth model developed by Penning de Vries et al. (1989) to simulate crop growth. The model use a suite of parameters for simulating plant growth, including, for example, carbon and nitrogen allocation, water requirements, light use efficiencies, and optimum yield. In addition, for each crop we estimate the fraction of total biomass that is harvested, which in turn indicates the amount of crop residue. Some values for these parameters were collected from the field measurements. Other parameters, such a thermal degree days required for crop to reach maturity were estimated by calibrating the model to the observed changes in biomass development.

Accurately crop growth simulation is a important for modeling soil N dynamics as crops take water and N from the soil during the growing season and hence alter the soil moisture and N regimes during and after the growing season that eventually affect the soil N pools and fluxes including nitrate leaching. In order assess impacts of alternative management for reducing GHG emissions, we first tested the DNDC crop models with observed crop yields for each site.

DNDC simulates crop growth based on a series of physiological and phenology parameters for each crop, which are stored in the crop library files. There are about 50 crops available in the DNDC library files. However, encountering new crops beyond the default library is common. To support users to easily create new crops or modify existing crops for simulation, we developed a sub-model “Crop Creator” in DNDC. This tool allows users to create a new crop library file for a new crop by defining its optimum yield, biomass partitioning, C/N ratio, water and heat requirement, and N fixation capacity. For this project, we create a new crop library file for the iceburg lettuce crop planted at the California site based on their optimum yields, biomass partitioning and C/N ratio observed *in situ*. Table 14 provides the list of crop parameters for the cotton, corn and lettuce crop model.

Table 14. DNDC crop parameters

Crop	Cotton	Corn	Lettuce
Plant Date	19-May	6-May	16-Jun
Harvest Date	15-Nov	11-Nov	11-Sep
Residue Fraction (%)	0.71	0.34	0.9
Yield (kg C/ha)	995	5460	1223
Rate_reproductive	0.01	0.025	0.03
Rate_vegetative	0.016	0.012	0.035
Psn_efficiency	0.4	0.4	0.48
Psn_maximum	45	60	35
Grain_fraction	0.11	0.52	0.64
Shoot_fraction	0.79	0.29	0.16
Root_fraction	0.1	0.19	0.2
Grain_CN	22	37	11.5
Shoot_CN	38	49	20
Root_CN	60	39	30
Thermal Degree Days	1200	2550	1400
Water_requirement	646	200	600
Max_LAI	4	5	4.2

Crop Yields: Using the 2009 climate data, we modeled crop yields and compared them with observed yields. The results for cotton we quite good, with modeled (361 kg C/ha) within a percent of observed (359 kg C/ha). The lettuce results were also good with modeled yield (1075 kg C/ha) within 12% of observed (1223 kg C/ha). For this comparison, we needed to estimate lettuce moisture content at harvest in order to compare carbon units. We assumed that lettuce dry matter weight was 7.8% of harvest weight (source: J. of Agriculture Science, Cambridge, 1980, 95:441-485. Our model results for corn were not as good. Reported yields were 5,187 kg C/ha. Our model results were 4091 kg C/ha, an underestimate of yields of 21%. DNDC tracks plant N demand and availability on a daily basis. Based on the model results, the discrepancy is due to insufficient nitrogen availability for plant growth. Due to some extreme temperature fluctuations (e.g. 40+ degrees in a couple days) in March 2009, the top soil layer underwent several freeze/thaw cycles which causes large denitrification rates, resulting in large losses of soil N. For comparison purposes, we ran the simulation using climate data from other years. Yields from these other year were significantly higher, for example for 1999 modeled yields were 4811 kg C/ha (only 7% lower than reported). Since the goal of this modeling work is to evaluate relative impacts of the various management scenarios, the impacts of the 2009 yield discrepancy will likely not be a factor in these comparisons.

Fallow Run: The DNDC estimates include emissions that result from the nitrogen accumulated in the soil from previous years (due to both crop residues and prior fertilization) plus the background emissions that occur from soil mineralization. In order to allow a direct comparison between the simplified models and DNDC a fallow run was included in the DNDC modeling and the emissions calculated during the fallow run were subtracted from the emissions during the focal year in order to estimate the emissions arising from the new fertilizer additions.

8.2.2 Results from DNDC Modeling

The results obtained from the DNDC modeling are shown in Table 15. To allow direct comparison with results obtained with other emission calculation methods the results here are shown with and without the “legacy” emission arising from fertilizer and crop residues accumulated in previous years, background emissions and with and without the additional emissions that arise due to atmospheric deposition at the site.

The direct emission from the pilot site in Iowa is clearly high. This high emission is a direct result of high organic carbon soils, the high precipitation in the analysis year and periods of rapid and dramatic temperature fluctuation.

Table 15. Results obtained from DNDC modeling of the three pilot sites.

		Arkansas	Iowa	California
Fertilizer N input	*kg N/ha*	107	207	219
Crop residue N input	*kg N/ha*	67	43	16
Direct				
N_2O flux	*t CO_2-e/ha*	0.5	11.5	0.5
Indirect				
Nitrate leaching loss	*kg N/ha*	4.3	6.3	37.1
Leaching emission	*t CO_2-e/ha*	0.02	0.02	0.13
NH_3 volatilization loss	*kg N/ha*	0.33	1.0	2.6
Volatilization emission	*t CO_2-e/ha*	0.002	0.005	0.012
Total Indirect Emission	*t CO_2-e/ha*	0.02	0.03	0.14
Total Emission	*t CO_2-e/ha*	0.50	11.55	0.66
Legacy/background				
Legacy Direct Emission	*t CO_2-e/ha*	0.4	1.2	0.0
Legacy Leaching Emission	*t CO_2-e/ha*	0.051	0.007	0.035
Legacy Volatilization Emission	*t CO_2-e/ha*	0.000	0.000	0.000
Total Legacy Emissions	*t CO_2-e/ha*	0.50	1.24	0.05
Total Emission Including Legacy Emissions	*t CO_2-e/ha*	1.00	12.78	0.71
Atmospheric N deposition				
Atmospheric N deposition	*kg N/ha*	63.02	38.69	0.75
Total Emission Including Atmospheric N Deposition	***t CO_2-e/ha***	**3.15**	**15.25**	**0.30**
NO flux	*kg N/ha*	0.32	1.2	0.5
N2 flux	*kg N/ha*	1.82	71.1	1.0
SOC dynamics (non-litter pools)	*t C/ha*	0.12	-0.56	0.04
Crop Yields	*t C/ha*	0.36	3.63	1.08

8.3 IPCC Tier 1 Method

Applying the IPCC Tier 1 method to the records of fertilizer usage on the three pilot study farms gives the estimated emissions detailed in Table 16.

As a Tier 1 method the emissions are directly proportional to the quantity of fertilizer added. California with the highest fertilizer addition has the highest emission of 1.37 t CO_2-e/ha (0.55 t CO_2-e/ac).

Table 16. Estimated direct and indirect emissions calculated for the pilot study farms using the IPCC Tier 1 method

		Arkansas	Iowa	California
Direct Emission kg CO_2-e/ha		0.50	0.97	1.03
Indirect Emission kg CO_2-e/ha	LEACH	0.05	0.10	0.10
	GASF	0.11	0.22	0.23
Total Emission t CO_2-e/ha		0.66	1.28	1.37

8.4 Comparison

The comparison between the estimated emissions under the three approaches is shown in Tables 17 to 19. The direct emission is half the value predicted by the simple methods for California but approximately an order of magnitude higher in Iowa. In Arkansas the three methods agree relatively closely.

Table 17. Comparison between the estimated DIRECT per unit area emissions using the three different methods across the three pilot sites

	Arkansas	Iowa	California
		t CO_2-e/ha	
IPCC Tier 1	0.50	0.97	1.03
DNDC Modeling	0.49	11.5	0.52
New Methodological Approach	0.55	1.26	0.98

In all cases simplified methods estimate much higher emission resulting from leaching than DNDC (Table 18). The difference was almost an order of magnitude for the sites in Iowa and Arkansas and though closer in California the new method still produced an estimate 50% higher than DNDC.

Table 18. Comparison between the estimated INDIRECT per unit area emissions using the three different methods across the three pilot sites

	Arkansas	Iowa	California
		t CO_2-e/ha	
IPCC Tier 1	0.16	0.32	0.33
DNDC Modeling	0.02	0.03	0.14
New Methodological Approach	0.14	0.26	0.21

For total emissions the DNDC estimate is 86% of the value predicted by the new method in Arkansas, 760% of the estimate for Iowa and 56% of the estimate for California.

Table 19. Comparison between the estimated total per unit area emissions using the three different methods across the three pilot sites

	Arkansas	Iowa	California
		t CO_2-e/ha	
IPCC Tier 1	0.66	1.28	1.37
DNDC Modeling	0.59	11.55	0.66
New Methodological Approach	0.69	1.52	1.18

9.0 A THEORETICAL ROAD TEST OF FERTILIZER EMISSION ACCOUNTING

9.1 Road Test Scenarios

We evaluated 12 different fertilizer management scenarios. These were all modeled without atmospheric nitrogen deposition as an input. These alternatives included:

- Use of time release fertilizers. Use of time release fertilizer can improve nitrogen use efficiency and potentially reduce total nitrous oxide production. We ran 4 scenarios related to the duration of the time release from field application. This included 6, 12 18 and 24 day release. These four scenarios are referred to as “6day”, “12day”, “18day”, and “24day”, respectively.

- Use of nitrification inhibitors. Nitrification inhibitors can reduce nitrous oxide emissions by reducing total denitrification. We ran the following 2 scenarios: nitrification inhibitor was 70% effective for 15 days (“Inhibit15”) and for 30 days (“Inhibit30”).

- Depth of fertilizer application. Injection of nitrogen fertilizers can improve nitrogen use efficiencies and thereby reduce N available for microbial nitrification and denitrification. We ran scenarios of injection depths of 5cm (“Depth15”) and 15cm (“Depth30”).

- Altered fertilizer application rates. We ran 4 scenarios for changes in fertilizer application rates representing two lower (70% [“Fert70”] and 90% [“Fert90”] of baseline) and two higher (110% [“Fert110”] and 130% [“Fert130”] of the baseline) application rates.

The three calculation approaches were applied across the 12 scenarios.

9.2 Results

The IPCC method and the new method proposed in this document only are able to give impacts of project activities that include a change in the quantity of fertilizer added. There is no means to evaluate timing of application, depth of application or the impact of nitrification inhibitors.

Across all methods decreasing the quantity of fertilizer decreases the net emission while increasing the quantity increases the emission (Table 20). The DNDC method, however gives a significantly greater impact for all states except Iowa. A 30% reduction in fertilizer use gives a decrease in N_2O emission equivalent to 0.68 t CO_2/ha in Arkansas and 5.69 t CO_2/ha in California, the comparable numbers under the IPCC method are just 0.20 t CO_2/ha and 0.35 t CO_2/ha.

Inhibitors in all cases led to a net decrease in greenhouse gas emissions when compared to the base case, however, the impact of time release fertilizers of more than 6 days has varying impacts, for example, 12, 18 and 24 day time release fertilizers actually increased emissions relative to the base case in Iowa.

Changing depth decreased emission in California but increased emissions in Arkansas. This reflects the literature that shows soil type influences whether deeper application leads to increases or decreases in emissions (reviewed by Millar et al 2010).

Table 20. Impacts of changes in fertilizer management practices relative to recorded baseline practices. Positive values indicate a net emission relative to the base case; the negative numbers (red) indicate that the emission is higher in the baseline case than in the "with-project" case

		Impact of change in management tCO_2e/ha											
		Change in quantity of applied fertilizer				**Time release fertilizers**				**Nitrification inhibitors**		**Depth**	
		70%	**90%**	**110%**	**130%**	**6day**	**12day**	**18day**	**24day**	**Inhibit15**	**Inhibit30**	**Depth5**	**Depth15**
ARKANSAS	IPCC	0.20	0.07	-0.07	-0.20								
	DNDC	0.68	0.62	-0.20	-1.21	0.39	0.70	0.66	0.67	0.11	0.11	-0.47	-0.41
	New Methodology	0.13	0.04	-0.05	-0.14								
IOWA	IPCC	0.39	0.13	-0.13	-0.39								
	DNDC	5.69	1.60	-1.33	-3.38	0.48	-0.68	-0.86	-0.59	0.07	0.07	-1.05	4.46
	New Methodology	0.43	0.16	-0.17	-0.57								
CALIFORNIA	IPCC	0.41	0.14	-0.14	-0.41								
	DNDC	0.20	0.07	-0.07	-0.19	0.05	0.06	0.07	0.10	0.03	0.03	0.08	0.03
	New Methodology	0.35	0.13	-0.14	-0.46								

10.0 SUMMARY

Both the IPCC Tier 1 method and the method that was proposed in this study have the advantage of being inexpensive to implement with a low requirement for expert technical support. However, unfortunately neither method can estimate nitrous oxide emissions with sufficient accuracy to qualify for carbon offset markets. This is principally because neither method can include the variables of precipitation and temperature that will significantly impact the rate at which emissions occur. In addition, both methods would limit projects to only altering rate of application rather than timing, placement or use of inhibitors. Rate reduction projects risk impacts on yields with concomitant uncertainty for farmers and therefore could be only a small proportion of the total future project portfolio.

11.0 RECOMMENDATIONS ON NEXT STEPS

Clearly neither the IPCC Tier 1 method nor the new method proposed here based on Bouwman et al (2002) could be considered sufficient for an offset project methodology that would be able to evaluate atmospheric impact of a broad range on fertilizer management practices. Therefore alternative approaches must be considered.

Millar et al. (2010) produced a recommendation for a protocol for nitrous oxide emissions from fertilizer. The proposed approach creates an IPCC Tier 2 method for calculating the emission that will result from a given fertilization. The method requires projects to calculate the maximum financial return for nitrogen addition and in the project case to apply the lowest profitable level. The Millar et al protocol only includes direct N_2O emissions and it only considers the rate not the timing or depth of fertilization nor the type of fertilizer. There is also no consideration of specific factors such as soil organic matter content or relative soil drainage that have been shown to directly impact emissions. Therefore, we would argue that the Millar et al approach though an improvement should also not be considered as a sufficient offset project methodology.

Van Groenigen et al (2010) suggest that nitrous oxide emissions from fertilization should be tied to N surplus. That is, the amount applied beyond the uptake ability of the crops is a key determinant of the N available for nitrification/denitrification and therefore N_2O emissions. The paper does not present a potential methodology but highlights the importance of not merely focusing on the direct relationship between quantity of N applied and N_2O emission.

It is our conclusion that nitrous oxide emissions resulting from fertilization are not susceptible to simple conceptual models or equations. Site specific factors and specific weather conditions must be considered if the atmospheric impacts are to be understood. Given that offsets from fertilizer management once verified will be equal to offsets from landfill gas or hydroelectric plants or any number of other sectors in which emissions and emission reductions can be measured accurately, it is important that estimates have a high degree of certainty and confidence associated.

Our recommendation therefore is that a methodology be developed based on the application of the DNDC model by projects. The model is highly calibrated and tested and considers each of the key determinants that will influence emissions from the agricultural soils. The DNDC itself is being continually improved and updated, both to further validate and enhance estimates and to make the model easier to use. These efforts will continue in parallel to work on methodology development and will enhance the strength and utility of the methodology.

We had initially avoided a model-based approach as we wished to avoid the costs that projects will incur through having to model both their baselines and with-project scenarios. However, we do not see a way around this if confidence is to be attained in fertilizer management projects and the example of tillage shows that emission reduction projects are the aggregate of a large number of farms rather than single small landholdings. In this aggregate situation the costs will be spread broadly and therefore will be relatively low.

A DNDC approach could use national databases on soil properties or for enhanced precision site specific measurements. A methodology could be written that allows both approaches but gives additional credit where measurements are undertaken.

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ANNEX 1: DNDC INPUTS

The following is a list of input data used by the DNDC model. Some data are required and some are optional.

Required Soil Data:

- ***Soil Texture***: Select soil type based on either its texture or clay fraction. There are 12 soil types including s*and, loamy sand, sandy loam, silt loam, loam, sandy clay loam, silty clay loam, clay loam, sandy clay, silty clay, clay, and organic soil.*
- ***Bulk density (g/cm^3)***: Bulk density (g/cubic cm) of top soil (0-10 cm).
- ***Soil pH***: pH of top soil.
- ***Clay content (0-1)*****:** Clay fraction of soil by weight.
- ***SOC at surface soil (0-5cm) (kg C/kg)***: Content of total soil organic carbon (SOC), including litter residue, microbes, humads, and passive humus at surface layer (0-5 cm).
- ***Slope (0-90)***: Slope of the soil surface in degree. The slope for a level soil is 0.

Optional Soil Data:

- ***Initial NO3(-) concentration at surface soil (mg N/kg)***: DNDC calculates default initial nitrate content at surface layer based on soil organic carbon content. You can replace the default with your observed data.
- ***Initial NH4(+)concentration at surface soil (mg N/kg)***: DNDC calculates default initial ammonium content at surface layer based on soil organic carbon content. You can replace the default with your observed data.
- ***Depth of water-retention layer (cm)***: If there is a water-retention layer existing within the simulated soil profile (i.e., 0-100 cm), define the depth of the layer. Water retention layer could be formed by soil compaction (common for intensively grazed pasture or a plow pan).
- ***High groundwater table***: If the groundwater table is seasonally above a depth of 50 cm, observations/estimates of daily water table depth as used.
- ***Field Capacity (0-1)***: Water-filled porosity (WFPS) at soil field capacity. texture is selected, default field capacity value will be given although it can be modified by users.
- ***Wilting Point (0-1)***: Water-filled porosity (WFPS) at soil wilting point.
- ***Macro-pores and bypass flow***: Are there macro-pores and bypass flow applicable to this soil (usually for tropical soils).

Required Crop Data

- ***Crop Type***
- ***Planting date***

- ***Harvest date***
- ***Is the crop a cover crop?***
- ***Fraction of leaves and stems left in field after harvest***: Specify a fraction of total above-ground crop residue (leaves and stems) left as stubble or litter in the field after harvest.

Optional Crop Data:

- ***Maximum grain production, kg dry matter/ha***: Grain production of the crop.
- ***Grain (or harvested) fraction of total biomass***: A fraction (0-1) of total biomass (i.e., grain + leaves + stems + roots), which is taken from the field at harvest.
- ***C/N ratio for grain***: Ratio of C vs. N contents in the grain of the crop.
- ***C/N ratio for leaf+stem***: Ratio of C vs. N contents in the leaves and stems of the crop.

Required Tillage Data

- ***How many applications in this year***: Number of tillage events per year
- ***Month/Day***: Date of each tillage event.
- ***Till method***: Define tillage depth for each tillage event.

Required Fertilizer Use Data

Fertilization is defined by specifying times, timing, method, fertilizer type and amount and special treatment for each application.

- ***How many fertilizer applications each year***:
- ***Month/Day of Fertilizer Application***:
- ***Application method***: Select surface application or injection (include depth for injection)
- ***Amount applied (kg N/ha)***:
- ***Type of fertilizer***
- ***Use of controlled release fertilizer***? If yes, then total days during for full release of fertilizer-N.
- ***Are nitrification inhibitor used?***: If yes, then estimates of its efficiency and effective duration (days) of the nitrification inhibitor are needed.

Required Manure Amendment Data

Manure application is defined by its timing, type and amount.

- ***How many applications in the year***: Number of applications in the year.
- ***Month/Day***: Date of each application.
- ***Manure type***] Select a type of manure. Five types of manure (e.g., farmyard manure, green manure, straw, liquid animal waste, and compost) are parameterized in DNDC.
- ***Amount (kg C/ha)***: Specify amount of manure as kg C per ha per application.
- ***C/N ratio***: Ratio of C/N in the manure. The default value is provided by DNDC but can be modified if data are avaialble

Required Irrigation Data

- ***How many irrigation events in the year***?
- ***Date of each irrigation event***.
- ***Irrigation type (sprinkler, furrow, drip tape)***
- ***Amount for each event (mm)***:
- ***Irrigation water pH and N content if known***

Additional Information:

- ***Lat,Lon of fields***
- ***Climate data (daily max and min temperature and precipitation). Solar radiation and wind if available.***

ANNEX 2: QUESTIONNAIRE: INFORMATION NEEDED FROM FARMER

All information will be treated as confidential and will not be shared or publicized

Name of data collector:…………………………………………

Title:…………………………………..Institution:………………………………………

Farmer's name……………………………

Address………………………………………

GPS (House)……………………………..

1. Does the farmer grow the crop on land that is ( ) owned, ( ) rented, ( ) share-cropped, ( ) communally farmed

2. Most common type of farming system (Please indicate date of planting):
( ) mono crop, specify type…………..

( ) intercrop, specify type…………..

( ) rotation, specify type…………..
( ) Cover crop? specify………………..

3. How is the ground prepared for planting?
( ) ploughed by tractor

( ) Other (specify)………………………….
Describe:……………………………………………………………………………..

4. How many times does the farmer till the sampled field?
Describe:……………………………………………………………………………………

5. Does the farmer fertilize the crop? Yes ( ) no ( ). If yes:

( ) Before/at planting describe method, formula, and quantity used:
……
………………………………………………………………………………………

( ) After planting describe method, formula, frequency, and quantity used for each field:……………………….

……
………………………………………………………………………………………

6. How is rate and location of application determined? :…………………………………………...……

……
………………………………………………………………………………………

7. Does the farmer use controlled release fertilizer in the sampled field? Yes ( ) no ( ). If yes, Please indicate total days during for full release of fertilizer-N.

8. Are nitrification inhibitors used in the sampled field? Yes ( ) no ( ): If yes, please indicate estimates of its efficiency and effective duration (days) of the nitrification inhibitor………
………………………………………………………………………………………………

9. Does the famer use manure? Yes ( ) No ( ) if yes, Please provide the following information:

a. Number of applications in the year……………………………………………
b. Date of each application………………………..
c. Type of manure……: farmyard manure ( ), green manure ( ), straw ( ), liquid animal waste ( ), or compost ( ).
d. Amount of manure kg C/ha/ application.
e. Ratio of C/N in the manure.

10. Summarize the cultural practices which are likely to impact crop production
……
……
……
……
……
………………………………………………………………………………………

11. Total crop area planted and level of production for the past five years.

Year	Hectares	Production
………….	…………………………………...	………………………………………..

………… ……………………………….. ……………………………………..
………… ……………………………….. ……………………………………..
………… ……………………………….. ……………………………………..
………… ……………………………….. ……………………………………..

12. Typical soil conditions in production area:

Soil:

a. Classification or type:………………………………………………………….
b. pH: ………………………………………………………………………………
c. slope: ……………………………………………………………………………..

13. Does the farmer collect rainfall data? ( ) yes ( ) No. If yes please provide the amount rainfall (inches) in the production area during the growing season:

14. Rainfall is considered excessive ( ), adequate ( ), or insufficient ( ).
Explain: ……………………………………………………………………………..

15. Are rains torrential to the degree of damaging the crop? yes ( ) no( )

16. Does the crop suffer from water logging (excessive amounts of standing water) at any time during the growing season? Yes ( ) no( )
Explain: ……………………………………………………………………………..

17. Does the area suffer from flooding during the growing season? Yes ( ) no ( )
Explain: ……………………………………………………………………………..

18. In case of drought conditions, is irrigation available? Yes ( ) no ( ). If yes, please provide the following information.

i. Number of irrigation events in the year……………………………………..
ii. Date of each irrigation event……………………………………………….
iii. Irrigation type (sprinkler, furrow, drip tape)…………………………..
iv. Amount for each event (mm): ……………………
v. Irrigation water pH and N content if known………pH………..N content

Explain: ……………………………………………………………………………..

19. Do you collect climate/weather data on the farm? Yes ( ) no( ) If so please provide the information: eg Temperature: Minimum………….Maximum………………..average………..

20. Is frost or cold temperature a constraint in this area? Yes ( ) no ( )
Explain: ……………………………………………………………………………..

21. Are high temperatures a problem for this crop in this area? Yes ( ) no( )
Explain: ………………………………………………………………………………..

22. What is the slope of most of the land in the growing area?

Very flat ( ), gently sloping ( ), moderately sloping ( ), steep ( ), very steep ( ), rolling ( ), mixed flat and sloping ( ).

23. How do the above ecological conditions generally affect crop production and/or yields?
………………………………………………………………………………..

24. Do the lands have tile drainage? Yes ( ) no( )

ANNEX 3: FIELD DATA COLLECTION

Soil sampling and processing.

All soil samples will be collected from the 0-10 cm soil layer. A soil sample (for soil carbon, nitrogen and texture determination) from each plot/area will be a composite of soil collected from locations within a plot/stratum. Soil sampling will be done at;

1. Before planting (Initial site characterization -before fertilization).

2. Immediately after harvesting.

Sample distribution will depend on the degree of variability in a given area. Stratified systematic sampling will be used to collect soil samples. Number of samples to be collected will be determined prior to going out to the field and after discussions with the farmer and assessment of field maps of the area to be sampled. Enough number of soil samples will collected from the sampled field to give us a 90% confidence interval of about 10% of the mean soil organic carbon (using Winrock procedure). The collected soil samples (600 grams per sample) will be sent to laboratory for soil carbon, nitrogen and textural analyses. Samples will be georeferenced with GPS receiver for repeatedly. This will allow for collection of samples in the immediately after harvesting from basically the same locations, even though we are compositing the cores for analysis. For each sampled plot/stratum, an additional two aggregated cores for determination of bulk density will be taken.

A rapid pH analysis of the sampled plots/stratum (as for bulk density) will be done in the field and information recorded on the field data sheet:

- Area to sample will be cleared of organic residues
- Using a soil tester probe, pH of 0-10 cm soil depth will be determined and recorded on the data sheet.

Field equipment needed for this task:

- Soil corer or probe,
- Ziploc bags (Soil carbon, nitrogen and texture samples),
- Non-breakable rod to remove soil from the soil core or probe.
- Permanent marking-pen.

Below is a field sampling form to be used for data collection.

Soil Sampling

Site…………………… Date………….. Time of Arrival… Departure……….

Chief crew……………………………………..

Notes:

Sample name/ID	GPS Coordinates	Notes (Include slope)
	Latitude	
	Longitude	
	Field pH	
	Latitude	
	Longitude	
	Field pH	
	Latitude	
	Longitude	
	Field pH	
	Latitude	

	Longitude	
	Field pH	
	Latitude	
	Longitude	
	Field pH	
	Latitude	
	Longitude	
	Field pH	
	Latitude	
	Longitude	
	Field pH	

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