WATER AND NUTRIENT MANAGEMENT IN A CHANGING CLIMATE:

A CASE STUDY FROM RURAL SRI LANKA

By

Elizabeth C. Stone

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Approved By:
George M. Hornberger
Jessica L. Oster

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Chapter I

INTRODUCTION

Rice is a staple food for over half of the human population. The domestication of the cereal grain in 10,000 BCE marks the advent of Asia's premier crop, and the tradition continues today across every continent but Antarctica (IRR, 2009). Rice-based farming is labor-intensive as well as water-intensive, making it vulnerable to changes in the climate, population, and the economy. The effects of climate change are already being felt in low latitude, less developed, agriculturally-based countries (*Schneider*, 2007). The water and agricultural sectors of Asian countries are the most at risk for climate change impacts (*Schneider*, 2007). As the effects of climate change become more apparent through temperature variations, sea level rise, changes in frequencies of droughts and extreme weather, and other disruptive events, developing, monsoon-dependent nations in Asia will be most vulnerable to disturbances (*Brooks et al.*, 2005). Food security, freshwater resources, and livelihood are so closely tied to these climatic changes that it is essential to understand how farmers can adapt.

Additionally it is important to consider the impact agricultural practices have on the environment. Paddy cultivation produces the greenhouse gases (GHGs) methane (CH_4) and nitrous oxide (N_2O); it emits carbon to the atmosphere from soil heterotrophic respiration and into the hydrosphere as dissolved organic carbon (DOC). Superfluous fertilization of paddy leads to nitrogen (N) leaching, which has serious implications for drainage water quality, including groundwater toxicity and health concerns for drinking water (*Choudhury and Kennedy*, 2005). It is vital to consider the trade-offs in producing the maximum amount of rice in such a way that does not compromise water quality or the concentration of harmful gases in Earth's atmosphere. This study explored various combinations of climate, soil, and paddy management and the resultant rice yields, GHG emissions, and N leaching levels, to determine best management practices that a farmer can follow without conceding his or her livelihood or the environment.

1.1 Rice and Water

In Asia irrigated water accounts for 90% of total diverted freshwater; rice cultivation uses 50% of this water. Reduced diversions for irrigation saves freshwater, reduces CH_4 emissions, and controls weed growth but the plant is very sensitive to water stress and high temperatures. Lowering flood levels at inopportune times in the growing season can reduce yield or ruin an entire crop, and cause the soil to aerate, hurting the field's potential to sustain paddy. Rice plants without sufficient water at the flowering stage undergo spike sterility, a condition where water stress reduces the number of spikelets that successfully complete pollination, fertilization, and grain development (*Ekanayake and Jayasuriya*, 1989). Flooded paddy is the cultural norm so as well as being practical for cultivation, so a change in this traditional management practice is not necessarily socially viable (*Talpur et al.*, 2011).

1.2 Rice and Fertilizer

Invented in the early 20th century, the Haber-Bosch process converts atmospheric N_2 to NH_3 and in turn synthetic N fertilizer. The development drastically changed global food production and the amount of reactive N in the global N reservoir. Increased cropland productivity is largely a result of the Green Revolution and the development of new crop varieties with a reliance on irrigation as well as the newly invented synthetic fertilizer. Natural N in an agricultural system comes from manure, crop residue, incorporation by weeds, atmospheric deposition, and biotic N fixation (*Galloway et al.*, 2008; *Li*, 2012).

Fertilizer accelerates yield to an extent but the more reactive nitrogen is added to agroecosystems, the more is lost to the atmosphere and water pathways, altering the natural N system (*Galloway et al.*, 2003). Tracer studies using N isotopes find that only 40-60% of fertilizer N is rapidly taken up by crops; the resulting fertilizer-derived soil N is lost to the atmosphere as NH_3, NO, N_2O, or N_2, or leached into the hydrosphere as NO_3^- (*Sebilo et al.*, 2013; *Smil*, 1999).

1.3 Sri Lanka

1.3.1 ADAPT-SL

This work is part of a larger, multidisciplinary research initiative called Agricultural Decision-Making and Adaptation to Precipitation Trends in Sri Lanka (ADAPT-SL) at Vanderbilt Institute for Energy and Environment (VIEE). Funded by the U.S. National Science Foundation, ADAPT-SL focuses on the environmental, institutional, social, and psychological influences on agricultural adaptation to climate change by paddy farmers in the dry zone of Sri Lanka. This portion of the project aims to gain a better understanding of how small-scale rice farmers in this region are adjusting their cultivation practices to deal with the effects of climate change.

1.3.2 Water

Sri Lanka has a tropical monsoon climate, with two rainfall seasons, a southwest monsoon from May to September and a northeast monsoon from December to February (*Wickramagamage*, 2009). The rainfall divides the country into three agro-climatic regions: the wet zone, the intermediate zone, and the dry zone (Figure 1.1). The wet zone receives annual rainfall of more than 2500 mm from both monsoons and the dry zone receives less than 1750 mm annually. Rice production dominates the dry zone while a mix of rice, tea, rubber, and coconut exists in the wet zone (*Chainuvati and Athipanan*, 2001).

Rainfall from the two monsoon events determines two distinct rice seasons, the main cultivation season or wet season, *maha*, from August to January, and the subsidiary cultivation season from February to July, *yala*, the dry season (*Zubair*, 2008; *Esham and Garforth*, 2012). The average rice yield over the two growing seasons in the dry zone is about 5 t/ha and in the wet zone 3.3 t/ha - a difference explained in part by the extensive irrigation system in the dry zone, shaded yellow in Figure 1.1 (*Weerakoon et al.*, 2011).

A number of traditional water management systems have evolved over thousands of years to store and allocate wet season water for cultivation in the dry season. As historically dry

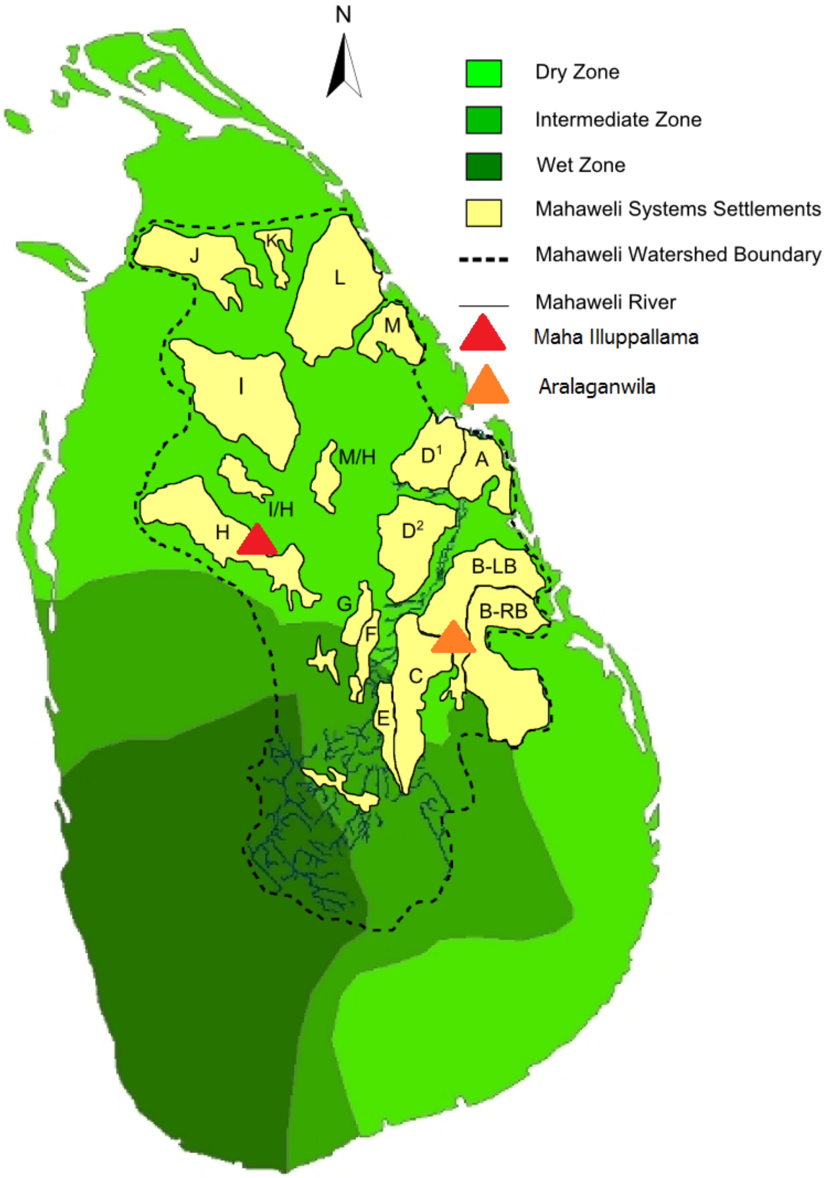


Figure 1.1: The Mahaweli River Watershed spans over 10,000 km^2 of the wet, intermediate, and dry zones of Sri Lanka. Mahaweli systems settlements receive irrigation water from a series of canals and reservoirs called tanks. Study sites in Aralaganwila (Polonnaruwa) and Maha Illuppallama (Anuradhapura) are designated by orange and red triangles.

areas have been developed, the government has stepped in to help manage irrigation systems, centralizing the canal networks and building infrastructure.

1.3.3 Rice

Rice has historic and cultural importance in the country as the crop has been cultivated since 160 BCE (IRR, 2009). Rice composes almost half of a traditional diet (DCS, 2007). The diversity of physical environments in Sri Lanka allows for a large number of rice varieties; at present there are 20 locally developed varieties grown in 99% of the country. Farmers choose a variety for the season based on water availability, length of growing period, and yield potential, as well as personal preference for consumption and market price (*Weerakoon et al.*, 2011). Sri Lanka is nearly self-sufficient in rice production, supplying 95% of the domestic requirement *Bishwajit et al.* (2013). The average rice yield of the country is 4.34 tons/hectare (t/ha), more than the global average of 4 t/ha (DCS, 2009; IRR, 2009). The crop is vital to maintaining food security; government polices work to maintain self-sufficiency in production through economic and agricultural measures including subsidies, insurance, and technological developments (*Bishwajit et al.*, 2013).

Water-intensive rice cultivation is particularly susceptible to climactic changes as the practice consumes more than 70% of total water allocated for food production in Sri Lanka *Henegedara* (2002). Lowland rice production in Asia is typically directly seeded in a field that is kept continuously flooded with 5-10 cm throughout the growing season (*Bouman et al.*, 2001). Interviews with farmers in the dry zone of Sri Lanka found the average flood depth is between 9 and 10 cm, depending on location relative to a centralized irrigation system (ADAPT-SL unpublished data).

Changes in rainfall patterns and temperature lead to new, often difficult, and expensive coping mechanisms; uncertainty in the farming schedule; and frequently crop failure. Farmers in rain-fed and minor systems that rely heavily on seasonal water frequently abandon *yala* cultivation due to reduced water availability and increased competition for water, decreased soil fertility, and land fragmentation (*Murray and Little*, 2000; Soi, 2005). Other adaptive management strategies in response to water scarcity include communal cultivation, selecting short duration or drought-resistant seeds, transplanting, dry seeding, and adding clay to the base and edges of paddy during field preparation. Farmers also practice the system of rice intensification, a method combining drought mitigation strategies, or choose to plant an alternate crop.

Additional adaptive options include no-till management and biomass residue retention. Cultivated lands have lower levels of soil organic matter (SOM), an important aspect of soil health, than comparable areas with natural vegetation where organic matter returns to the soil. Tilling aerates the soil and breaks up the organic residues, making them accessible to microbial decomposition. While tilling can raise SOM levels, other impacts of the practice are not beneficial to the soil or increased carbon inputs to the atmosphere as no-till management sequesters carbon and affects albedo and evapotranspiration. Studies show that no-till reduces yields by around 5% but requires less labor and reduces energy costs, while improving soil quality and minimizing erosion. Farmers are encouraged to practice no-till management along with other conservation agriculture practices like leaving crop residues in fields and rotating crops. Removing crop biomass from the field reduces CH_4 emissions but it is labor and time intensive. The biomass has few other uses so it is generally burned, a practice that releases GHGs and particulate matter *Pittelkow et al.* (2014).

Another alternative management strategy is alternate wetting and drying (AWD), a water-saving technique that allows a field to dry to a certain extent between irrigation events. AWD is widely accepted as the best management practice for reducing GHG emissions from irrigated fields; by lowering flooding levels and the duration of saturation events, the technique reduces CH_4 emissions by about half that of continuous flooding *Schneider* (2007). AWD is not always a viable option. Lowland areas where soils cannot be drained at frequent intervals are not suitable for the practice, and farmers who do not have control over the timing of water releases for field irrigation cannot use AWD. If rainfall exceeds water lost to evapotranspiration and seepage, the field will be unable to dry during the growing period, a major factor in AWD cultivation. As a result, due to the tropical monsoon climate and the irrigation management structure, not all Sri Lankan farmers can practice the technique IRR (2009). However AWD, even without superfluous fertilization, enables farmers to save irrigation water by 25-50%, improve yield, and lessen environmental impacts even in an unpredictable environment (*Styger et al.*, 2011; *Ekanayake and Jayasuriya*, 1989).

Chemical fertilizer innovations have increased rice yields over the past several decades but also led to an increased dependence on external inputs and higher costs of cultivation (Ulluwishewa, 1991). Sri Lanka is one of the highest intensity fertilizer users in Asia. Studies show that most farmers in the dry zone apply larger amounts of N fertilizer than those in the intermediate and wet zones (Wijayartna and Weerakoon, 1996). All the farmers interviewed in the dry zone sites for this study reported using fertilizer for both cultivation seasons in recent years (ADAPT-SL unpublished data). While the Sri Lankan Department of Agriculture publishes recommended fertilizer application amounts and timing for cultivation that vary for each climate region and rice variety, studies show that Sri Lankan farmers use an excess of six times the recommended fertilizer per growing season *Young et al.* (2009). Farmer surveys (ADAPT-SL unpublished data) suggest farmers are applying more N fertilizer than needed or recommended because of its cheap cost, in part due to government subsides of fertilizer that have been in place since 1962 (*Weerahewa et al.*, 2010).

Chapter II

BACKGROUND AND OBJECTIVES

2.1 Sri Lanka

The island nation of Sri Lanka provides a microcosm in which to study coupled human and environmental systems and the mechanisms necessary for agricultural adaptation to climate change. The agricultural sector employs 66% of the population and rice production occupies over 17% of agricultural land in Sri Lanka (*Wijeshinghe and Pushpakumari*, 2007; DCS, 2011). Almost 2 million farmers depend on paddy for livelihood as more than 30% of total labor force is directly or indirectly involved in the paddy sector (DCS, 2007; *Weerahewa et al.*, 2010).

The country's dependence on rice cultivation makes it particularly susceptible to climate disturbances. Traditional paddy farming depends on large inputs of water to sustain the plant and keep weeds at bay, and seasonal monsoons provide predictable water sources. However as climate patterns become more unpredictable with the southwest monsoon starting earlier, the northwest monsoon starting later, and slight shifts in spatial rainfall patterns, farmers have difficulty following traditional management practices and obtaining sufficient yields (*Jacobi*, 2014). In 2014, the country experienced the worst drought in recorded history, severely affecting rice harvests.

2.1.1 STUDY AREA: Dry Zone/Northwest Region

The study area, the North Central Province, is in the central part of the dry zone and contains a large portion of the Mahaweli River Watershed (MRW) (Figure 1.1). More than 65% of the province's residents are dependent on agriculture and agriculture-related activities. The dry zone is historically prone to water shortages so climate risks are not new to farmers in the area; however recent changes to annual patterns make these farmers even more vulnerable to changes in temperature and precipitation (*Senaratne and Scarborough*, 2011). In this region, paddy cultivation is under three different irrigation systems: major, minor, and rain-fed (*Prasanna et al.*, 2011). Varying water availability and access in the irrigation systems affect farmers' decision-making and cultivation practices. In all agroecological regions of Sri Lanka, farmers typically cultivate around the onset of monsoon rains to best use the rainfall and save irrigation water for dry periods (*De Silva et al.*, 2007).

For centuries farmers have stored rainfall in tanks, called *wewas*, for irrigation, a practice that still occurs in rain-fed systems. Another water storage strategy came about in the 1960s when Sri Lanka began to develop a number of high capacity, centrally-managed irrigation systems that fall under the jurisdiction of the national government. One such initiative was the Mahaweli River Authority, as part of the Mahaweli Accelerated Development Program, to divert water from the Mahaweli River, the largest river in the country, for hydropower, irrigation, and settlement of the dry northeast region. The Mahaweli headwaters are located in the hill country southeastern portion of the country in the wet zone and flow towards the eastern coast. The river's drainage basin spans one-fifth of the country, making it the largest river in Sri Lanka. Today the developed Mahaweli canal system provides the majority of irrigation water while the rest of the region is organized under traditional rain-fed schemes.

Two sets of crop management practices, a Mahaweli scheme and a traditional scheme, differ in terms of governance, irrigation method, and geographic location. Farming practices in Mahaweli schemes are relatively consistent across the Mahaweli systems (yellow areas in Figure 1.1). Agricultural extension agents provide advice on seed variety and crop management depending on the growing season and water availability from the MRW irrigation network. In contrast, farmers in the ancient, *wewa*-cascade systems tend to follow more traditional farming practices called *purana* based on generational knowledge and farmers almanac-type predictions. *Purana* practices are more localized than that of the Mahaweli, but they all depend on irrigation water from either rainfall or releases by government officials from traditional tanks into irrigation canals. This work examined major and rain-fed irrigation systems in the dry zone under irrigated, Mahaweli paddy management and traditional, rain-fed management.

2.1.2 STUDY SITES: Aralaganwila (Polonnaruwa) and Maha Illupallama (Anuradhapura)

The study sites Aralaganwila, in the Polonnaruwa district, and Maha Illupallama, in the Anuradhapura district, were chosen based on ADAPT-SL survey sites and available longitudinal climate data from the Sri Lanka Meteorological Department (Figure 1.1). Early irrigation systems reached Anuradhapura in the tenth century and Polonnaruwa in the eleventh century but they still support a large number of rain-fed systems as well (*Zubair*, 2005).

Therefore these areas are ideal to simulate the two different irrigation schemes with limited political or geographical differences.

2.2 Objectives

This paper focuses on potential changes to cultivation practices by small-scale Sri Lankan paddy farmers to adapt to drought as a result of climate change. The study explored how rice yields, GHG emissions, and N leaching vary under a range of typical rice farming scenarios for two Sri Lankan environments in order to determine the ideal practices that a Sri Lankan farmer can follow without compromising his or her livelihood or the environment.

Chapter III

METHODS

3.1 DNDC Model

The primary method for this study is a modeling approach to simulate paddy-based agricultural systems with different irrigation and fertilizer practices in Sri Lankan soil and climate conditions. The DeNitrification-DeComposition (DNDC) model is a process-based model that incorporates existing soil, climate, and crop management data with the carbon and nitrogen biogeochemical cycles and the primary ecological factors in an agricultural system (*Li et al.*, 1992)(Figure 3.1). These main factors drive sub-models of soil climate, crop growth, decomposition, and denitrification. The model outputs account for emissions of the GHGs nitrous oxide (N_2O), nitrogen oxide (NO), nitrogen gas or dinitrogen (N_2), methane (CH_4), and carbon dioxide (CO_2), as well as the volume of N leaching and rice yield. The model runs on a daily time step and provides daily and annual results. Experimental results from measurements in paddy fields are not available for this study to test the adequacy of the model; therefore fairly large uncertainties in absolute values of nitrogen losses and GHG emissions are expected. Experimental analysis is necessary to validate the model results in Sri Lanka but work in India and Bangladesh in rice-based systems validated the model in these locations (*Babu et al.*, 2005). This research shows that DNDC can serve as a tool to determine which farming practices are best suited to the changing Sri Lankan environment

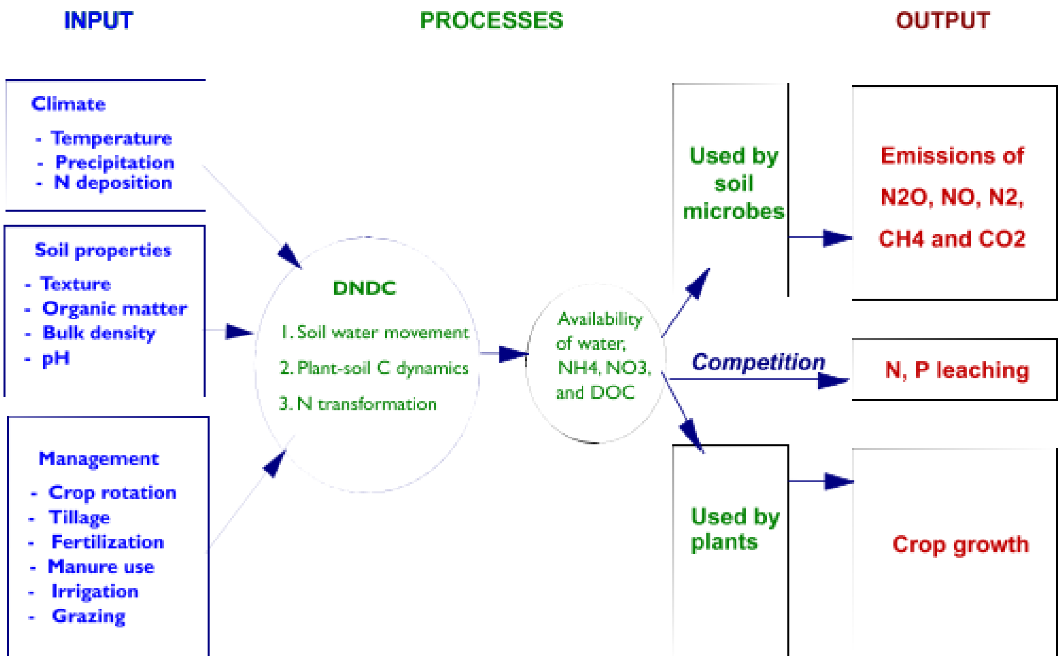


Figure 3.1: DNDC model inputs, processes, and outputs (*Li et al.*, 1992).

and it sets the stage for applying the model across Sri Lanka so that should it become feasible to take field measurements, future work could test the model results.

DNDC simulates the growing area as one hectare (ha), an average plot size for cultivation in Sri Lanka as 70% of farmers are small holders with less than 1 ha of land (*Prasanna et al.*, 2011). The model ran with constant inputs of climate and farming managements for 20 years before the simulation years. This technique, the spin-up run, allows the model to achieve near-steady state conditions, in particular in SOC pools, before the simulation years begin. A fixed default does not apply to every location and climate scenario so the spin-up is used to set the initial conditions for each site, repeating the environmental conditions of the 20 years before recording results for the 20 years simulated (*Fumoto et al.*, 2007).

First, the DNDC model was used to examine how variations in climate and soil affect rice yields, GHG emissions, and the percolation of nitrogen species into groundwater and canals at both study sites, holding the crop management schemes constant for both sites. After these runs, the management practices of farmers in Mahaweli systems were compared to traditional practices, both in the environment of Maha Illuppallama. The second group of runs removed environmental variability and reduced the comparison of outputs to management practices like irrigation technique, fertilizer application, tilling, and growth duration of the crop. Finally, the third set of runs tests alternative management strategies to drought, by simulating both AWD and the inability to grow rice in the secondary growing season.

3.2 Data for Regional Synthesis Approach

Input requirements for the sub-models in DNDC were as follows.

3.2.1 Climate

Temperature and precipitation data acquired from the Meteorological Department of Sri Lanka provided the climate inputs to the model. Daily rainfall and maximum and minimum temperature records were from 1991 to 2010 from the climate stations in Aralaganwila and Maha Illuppallama (Figures 3.2 and 3.3).

Other climate inputs required for the simulation were nitrogen deposition, atmospheric NH_3 and $C0_2$ concentrations. Based on the nitrogen deposition value for Sri Lanka and the annual rainfall in the dry zone, the N concentration in rainfall in Sri Lanka is 0.74 mg N/L (*Phoenix et al.*, 2006; *Zubair*, 2002). Model default values were used for atmospheric NH_3

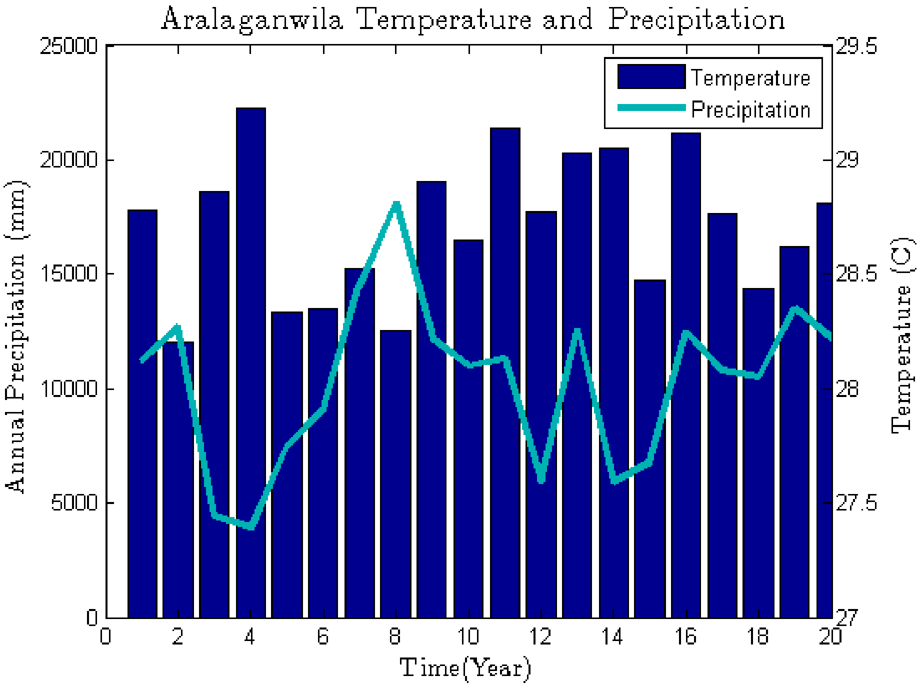


Figure 3.2: Annual precipitation and mean temperature for Aralaganwila.

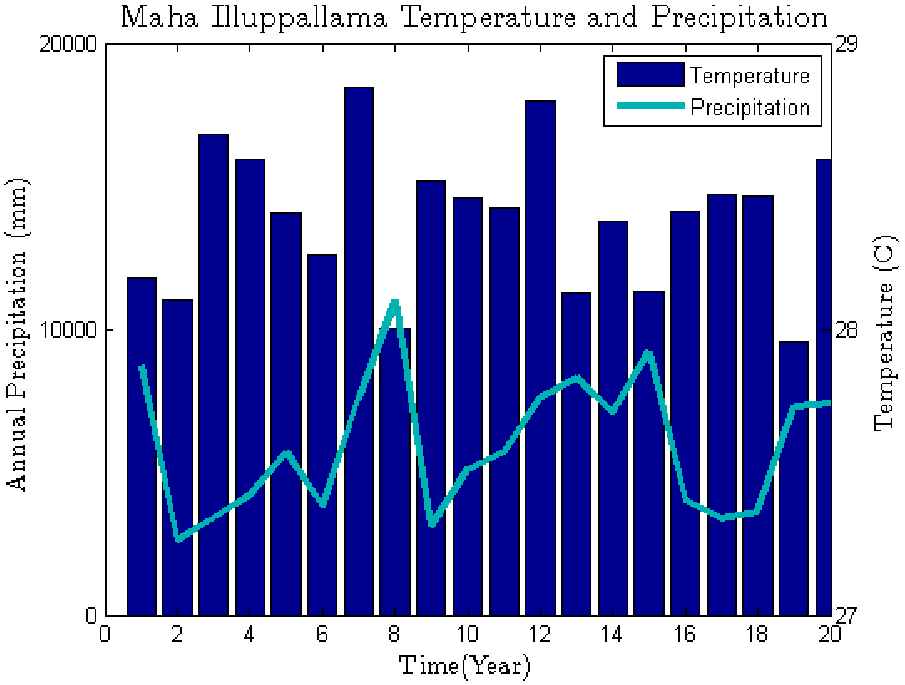


Figure 3.3: Annual precipitation and mean temperature for Maha Illuppallama.

concentrations and values from the National Oceanic and Atmospheric Administration were used for the atmospheric concentration and increase of CO_2.

3.2.2 Soil

Soils in the dry zone of Sri Lanka are typically reddish brown clays, low humic gley soils, and immature brown loams; they vary significantly across the region. Maha Illupallama soils have a sandy clay loam texture and are imperfectly drained. Medium hydraulic conductivity leads to high water losses by seepage and percolation but the high clay content of the soil allows it to retain a fair amount of available water. Provided suitable water, the soil is ideal for growing rice and can foster very high yield with adequate water and nutrient additions. In comparison, soils from the Aralaganwila region are moderately well drained. These soils are capable of supporting most crops, including rice. The clay content and the high cation exchange ratio result in high moisture-retaining capacity for both irrigated and rain-fed agriculture (Soi, 2005).

Soil physical properties required for simulation include soil texture, clay content, field capacity, wilting point, pH, porosity, initial soil organic carbon (SOC) content, saturated hydraulic conductivity, and bulk density. Soil maps from the University of Peradeniya were the primary reference for soil inputs in the model, partially validated with field work in May 2013 (*Dassanayake and Mapa*, 2007). Soil samples from the study areas were analyzed for pH using a LaMotte Soil pH Test Kit (Item 4EVY4). A soil quality field test kit from the Ohio Agricultural Research and Development Center and The Ohio State University was used to test for soil organic matter (SOM) and available nitrogen. Using rudimentary field analysis the soils were evaluated for texture and clay fraction. GPS locations of the soil sample sites and corresponding results are in Appendix A.

DNDC provides defaults for additional soil information based on the soil type and SOC, a value calculated based on the SOC at the surface of the soil from (Soi, 2005).

3.2.3 Crop Management

Farm management practices in the model include land preparation, water management, crop choice, variety duration, fertilizer application, and planting and harvesting dates. This simulation includes 3, 3.5, and 4-month varieties of rice in both rain-fed and irrigated systems. Visits to the field sites, information from government agencies, and the literature provided inputs to this portion of the model.

The ADAPT-SL research group collected data on crop management on multiple trips to the country and pilot studies in 2011, 2013, and 2014, of over 200 households in the dry zone. Structured surveys, formal interviews, and focus groups with farmers, agricultural extension officers, government officials, and nongovernmental agencies collected accounts of farmer attitudes, beliefs, and behaviors. Records were also available from unstructured interviews with a representative sampling of farmers in the study area to whom questions were directed regarding inputs into the model such as fertilizer timing and application practices and irrigation schedule (ADAPT-SL unpublished data).

Recommended fertilizer schedules from the Sri Lankan Department of Agriculture provided information on amounts, timing, and type of fertilizer to add to paddy (Appendix B). Schedules are based on the duration of the rice variety and location in an irrigated or rain-fed system. Fertilizer applications are fairly similar for the cultivation seasons except that *maha* includes an application of zinc sulfate and requires additional fertilizer when the seed is a long duration variety. The schedules, along with a paddy cultivation sequence from the Irrigation Department (Sri Lanka Irrigation Department, unpublished data), provided information to create a schematic of the paddy cultivation schedule (Figure 3.4) and a cultivation calendar (Table III.1). Based on the calendar, various combinations of fertilizer type and timing, along with irrigation techniques and other management options, simulated the scenarios listed below. The actual fertilizer applications emulated that of a farmer using an excess of six times the recommended fertilizer application, the low end of a range of application amounts farmers are known to use in Sri Lanka (*Young et al.*, 2009; *Weerahewa et al.*, 2010; **?**). The literature and the Sri Lankan Department of Agriculture provided information on tilling, such as tools and timing. A mamoty is the hand tool typically used to dig and prepare the land for cultivation used in Southeast Asia (*Fernando*, 1982). Knowing this, when simulating conventional tilling, the option selected in DNDC was tilling with a disk or chisel at about 10 cm depth.

Nitrate and ammonium concentrations were used to determine the inorganic N in irrigation water, as rice plant roots primarily take up N from the soil as dissolved $NO3^-$ and NH_4^+ ions. For the model runs the floodwater had 0.245 kg N/ha for conventional flooding and 0.123 kg N/ha for marginal flooding (*Young et al.*, 2009).

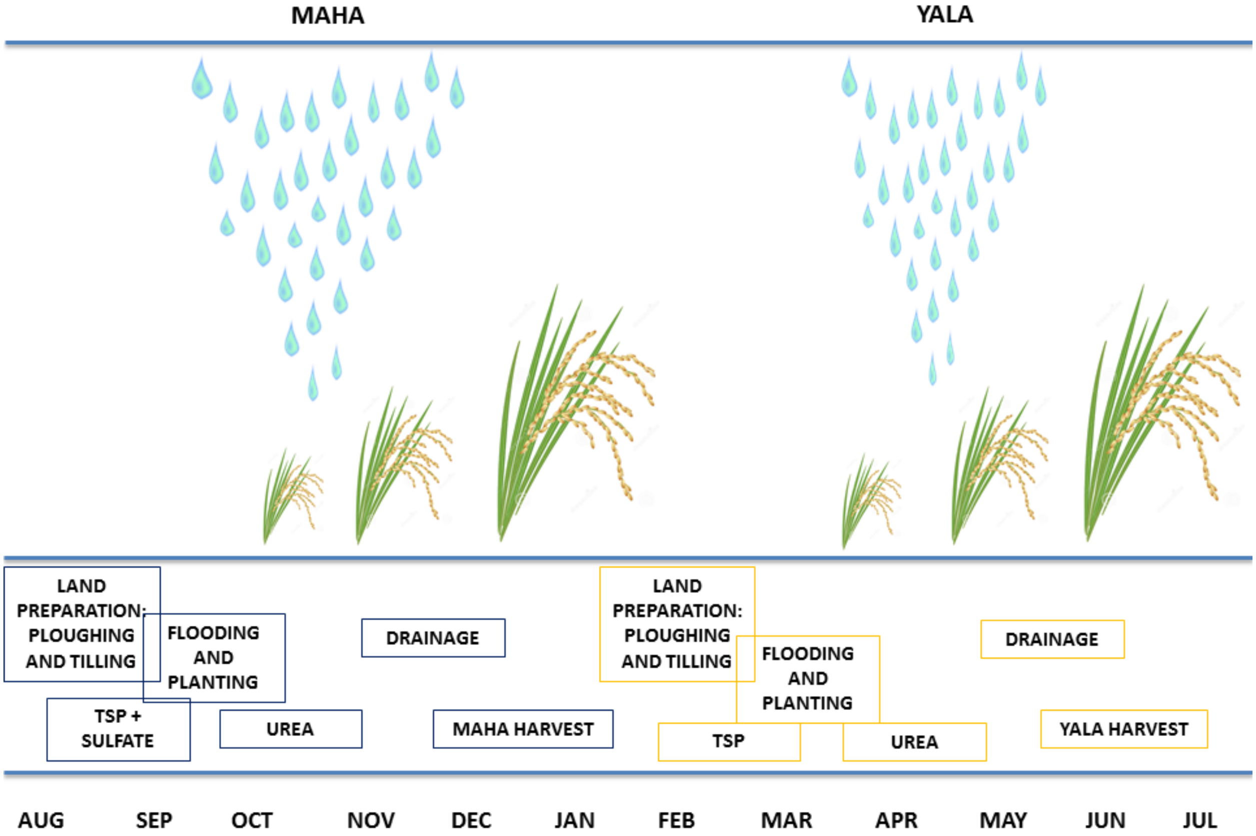


Figure 3.4: An annual paddy cultivation sequence in Sri Lanka. Blue boxes highlight activities related to *maha* cultivation while orange boxes correspond to *yala*. Triple superphosphate (TSP), zinc sulfate, and urea are types of fertilizer.

DAP	Field Management Practice
-19	Ploughing/Tilling
-18	TSP+ Zinc sulfate
-8	Flooding
0	Planting
21	Urea
35	Urea
49	Urea
56	Urea
86	Drainage
105	Harvest
135	End Harvest

Table III.1 Cultivation calendar of field management practices for a 3.5-month rice variety based around the DAP (date after planting).

Farmers in Sri Lanka frequently line the bottom of the paddy and the sides of the field, known as bunds, with clay to reduce water loss, so the water leaking rate used in the model is that of a clay soil in a rice flooded system (*Sivapalan and Palmer*, 2014). The DNDC model only has two options for flooding so irrigation water depth in the paddy is restricted to conventional, 10 cm, and marginal, -5 to 5 cm. Based on responses to ADAPT-SL surveys, conventional flooding levels were used for calculations and model inputs. The AWD schedule is the only scenario that uses marginal flooding depths.

3.3 Environmental Variability

Gradients in precipitation, temperature, and soil extend across the wet, intermediate and dry zones and within each region, leading to environmental variability across the island. An investigation of environmental differences in Maha Illuppallama and Aralaganwila involved

Parameter	Input Value Araganawila	 Maha Illuppallama
Soil texture	Sandy clay loam	Sandy clay loam
Bulk density (g/cm^3)	1.39	1.40
pH	6.0	6.5
Clay fraction	0.05	0.28
Hydraulic conductivity (m/hr)	1.51	0.49
SOC at surface (kg C/kg soil)	0.0081	0.0076
Initial NO_3^- at surface (mg N/kg soil)	0.5	0.5
Initial NH_4^+ at surface(mg N/kg soil)	0.05	0.05
Simulated years	20	20

Table III.2 Selected soil parameters used in DNDC.

varying soil and climate parameters in DNDC to simulate the two settings, while holding the crop management schemes constant for both systems. The main input parameters for both settings used in the soil sub-model are listed in Table III.2. The environmental scenarios are both in a rain-fed system with 3 and 3.5-month rice varieties. The model simulated both recommended and actual fertilizer applications and conventional tilling and no-till methods in Aralaganwila and Maha Illuppallama.

3.4 Management Variability

DNDC runs next removed environmental variability and reduced the comparison to crop management and various irrigation schemes by running the model in a Maha Illuppallama setting. The climate and soil sub-models in DNDC were set with the environment of Maha Illupallama to remove environmental variability and reduce the comparison of outputs to management practices in irrigated Mahaweli, traditional rain-fed, and AWD systems. Fig-

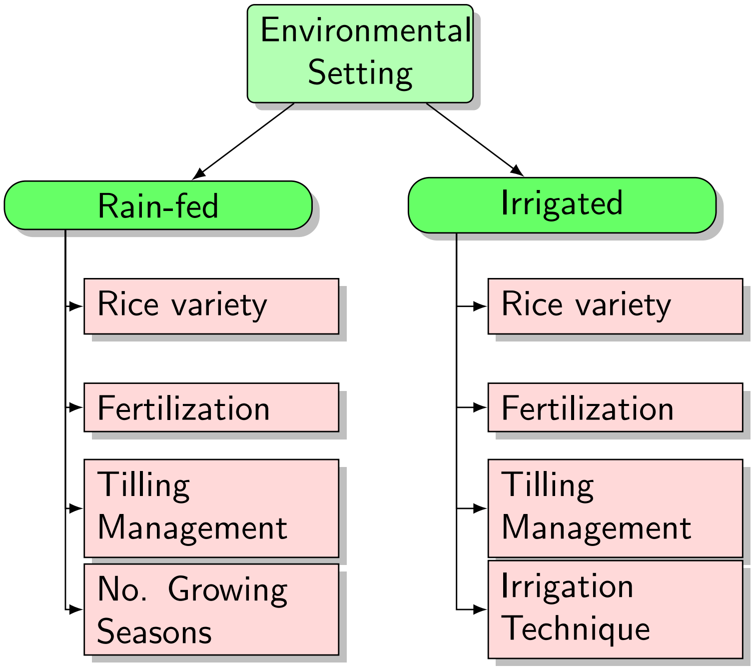


Figure 3.5: Management options for a farmer in Sri Lanka. Based on the paddy's location in a rain-fed or irrigated scheme (green), the farmer must make management decisions for each of the listed options (pink).

ure 3.5 shows the management decisions that lead to various scenarios. The selected crop management scenarios are as follows.

1. Irrigated, 3.5 and 4-month varieties, recommended fertilizer application amounts and timing, conventional tilling
2. Irrigated, 3.5 and 4-month varieties, actual fertilizer application amounts and timing, conventional tilling
3. AWD irrigation, 3.5 and 4-month varieties, recommended fertilizer application amounts and timing, conventional tilling

4. Rain-fed, 3.5-month variety, recommended fertilizer application amounts and timing, conventional tilling

3.5 Sensitivity Analysis

A sensitivity analysis, using a Monte Carlo simulation, was conducted to prioritize the environmental effects on the model outputs. Monte Carlo analysis involves randomly adjusting specific parameters thousands of times to get a statistical distribution of outputs. This work tested multiple parameters to determine the most sensitive factors for N leaching, yield, and the combined GHG emissions of N_2O, NO, NH_3, and N_2.

A general sensitivity analysis of the results of Scenario 1, an irrigated system in Maha Illuppallama with recommended fertilizer applications and conventional tilling, was performed using the DNDC model's Monte Carlo function. Appendix C shows the parameters and their respective ranges in the Monte Carlo simulation. The Monte Carlo outcomes were separated into two categories to analyze the results based around a set value of N leaching, yield, and GHG emissions. Hornberger and Spear use a technique of setting this value, a system's problem-defining behavior, and defining a classification algorithm to determine if each model output is a behavior (B) or not a behavior (NB) (*Hornberger and Spear*, 1981). Values less than the behavior were considered a NB, and values greater than or equal to the behavior were a B. The selected behavior values for N leaching, yield, and GHG emissions were 65 kg N/ha/y, 4,100 kg C/ha/y, and 36 kg N/ha/y, respectively. Cumulative distribution functions (CDFs) of each output's behavioral classification provided information on which parameters were the strongest determinants of the behavior. The distance between the two CDF plots shows how similar the effect of the parameter is on B and NB outputs.

Each model output, still classified as B or NB, was displayed in a 3-D space to visualize the impact of each selected parameter on the model outputs.

Chapter IV

RESULTS

4.1 Environmental Variability

Holding management practices constant for a rain-fed paddy in Aralaganwila and Maha Illuppallama settings resulted in a comparison of the environments and their impact on DNDC outputs (Figures 4.1 and 4.2). CO_2 emissions range from 10-30 kg C/ha/y in Aralaganwila and 25-50 kgC/ha/y in Maha Illuppallama. N_2O emissions range from 0-30 kgN/ha/y in Aralaganwila and 5-40 kgN/ha/y in Maha Illuppallama. A slightly warmer, wetter climate in Aralaganwila may be the cause for these variations, particularly in GHG emissions (Figures 3.2 and 3.3). Fluctuations of CO_2 and N_2O over time could be the result of differences in annual precipitation and temperature. CH_4 emissions are negligible in both settings. In the DNDC model, it is assumed that CH_4 production begins after the end of N_2O production; this may be the reason for such low values of CH_4 production (*Li*, 2012). Soil variability had the least effect on DNDC outputs of the three sub-models; this was expected, as there was little difference in the soils of the study sites. Due to the heterogeneous soils across Sri Lanka, it would be prudent to keep the soil sub-model in mind when performing these tests in other locations.

Yield was higher in Maha Illuppallama than Aralaganwila by a tenth and N leaching values were lower by a factor of three. When varying fertilizer amounts and tilling manage-

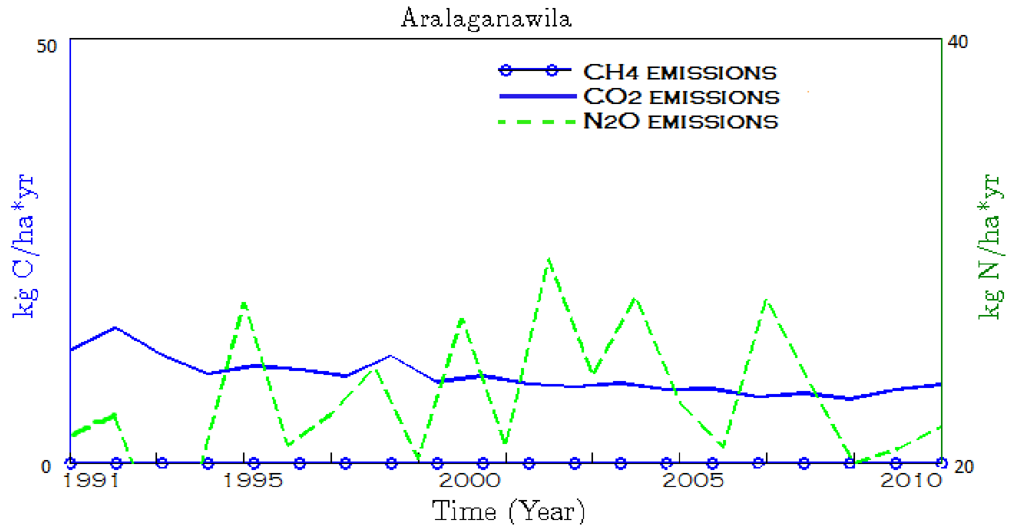


Figure 4.1: Simulated annual carbon dioxide, methane, and nitrous oxide fluxes from an Aralaganwila paddy with an area of one ha.

Management Options and Outputs for Aralaganwila: Rain-fed		
yield (kgC/ha/y) N leaching (kgN/ha/y)	**Recommended Fertilizer**	**Actual Fertilizer**
Conventional Tilling	93,000 3,000	93,000 11,000
No-Till	93,000 3,000	x

Table IV.1 Management options and resultant DNDC outputs for a rain-fed system in Aralaganwila. The numbers are rounded to the nearest thousand.

ment in both settings, yield remained the same. N leaching increased by a factor of four as a result of fertilizer additions. In these rain-fed settings yield and N leaching were only slightly affected by environmental differences and not at all by tilling technique. Increases in fertilizer had no influence on yield but increased N leaching from the paddy (Tables IV.1 and IV.2).

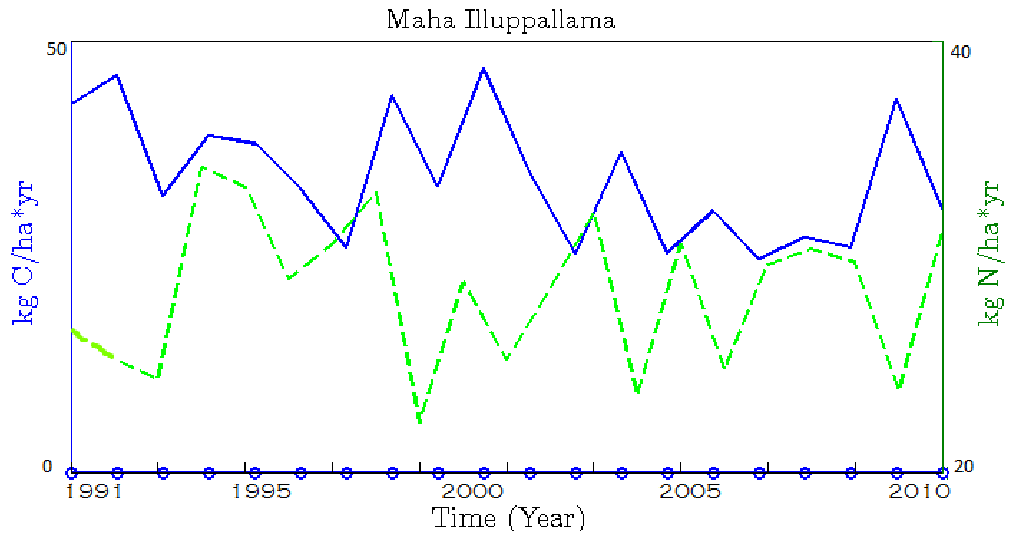


Figure 4.2: Simulated annual carbon dioxide, methane, and nitrous oxide fluxes from a Maha Illuppallama paddy with an area of one ha.

Management Options and Outputs for Maha Illuppallama: Rain-fed		
yield (kgC/ha/y) N leaching (kgN/ha/y)	**Recommended Fertilizer**	**Actual Fertilizer**
Conventional Tilling	104,000 2,000	104,000 9,000
No-Till	104,000 2,000	x

Table IV.2 Management options and resultant DNDC outputs for a rain-fed system in Maha Illuppallama. The numbers are rounded to the nearest thousand.

4.2 Management Variability

Model results (Table IV.3) in Scenarios 1 and 2 compare recommended fertilizer applications to those application amounts known to be used in the field by Sri Lankan farmers. Scenario 3 is that of an AWD irrigation scheme, best compared to a traditionally irrigated system in Scenario 1. The results in Scenario 4 are from cultivation in a water-scarce, rain-fed setting with only *maha* cultivation, that can again be considered against the outputs of Scenario 1 where both *maha* and *yala* cultivation occur in an irrigated system without water stress.

Comparing outputs of a rain-fed system and corresponding agricultural practices (Table IV.2) to those of an irrigated system (Scenario 1) in the same environmental setting, rain-fed cultivation led to only two-thirds the yield. N leaching values were an order of magnitude greater in rain-fed schemes than irrigated. Reducing the depth of water in the field and frequency of irrigation events with AWD techniques (Scenario 3) compared to traditionally irrigated (Scenario 1) resulted the same yield and N leaching values.

Increasing fertilizer inputs magnified the amount of N leaching into groundwater resources, going from 0 to 2,000 kgN/ha/y, without changing rice yield (Scenario 2). CH_4 emissions increased by a factor of seven and N_2O by two.

Unlike the environmental comparisons, the management results do not demonstrate the DNDC assumption that CH_4 production begins after the end of N_2O production (Li, 2007). When water inputs are high, the breakdown of organic carbon in DNDC produces CH_4. The addition of water to the system from irrigation events, which could also happen with an increase in precipitation, resulted in large CH_4 emissions (Scenarios 1 and 2), whereas the emissions from rain-fed and AWD settings are 0 kgC/ha/y. Reducing the depth of irrigation and frequency would change this, demonstrated in this study by AWD, which reduced emissions of CH_4. The huge CH_4 difference between DNDC results for Scenarios 1 and 2 is most likely due to fertilizer additions.

Traditional irrigation led to soil CO_2 emissions that were greater than those of AWD by a factor of a thousand, and even greater for a rain-fed system (Table IV.3). The longer the irrigation period and the greater the flooding depth, the more CO_2 emissions increased.

Finally, when drought in a rain-fed environment was quantified as the inability to grow rice in the secondary growing season, *yala*, results showed only half the rice yield as expected. Carbon emissions from both C_4 and CO_2 decreased but N_2O emissions and N leaching increased.

Model Output	**Yield (kgC/ha/y)**	**N_2O flux (kgN/ha/y)**	**CH_4 flux (kgC/ha/y)**	**Soil CO_2 flux (kgC/ha/y)**	**N leaching (kgN/ha/y)**
Scenario 1	180,000	100	400	14,000	0
Scenario 2	180,000	300	3,000	14,000	2,000
Scenario 3	180,000	100	0	4,000	0
Scenario 4	55,000	300	0	1,000	2,000

Table IV.3 DNDC outputs for various cultivation and irrigation scenarios in Maha Illuppallama. The scenarios are: Scenario 1: Irrigated, recommended fertilizer application amounts and timing; Scenario 2: Irrigated, actual fertilizer application amounts and timing; Scenario 3: AWD irrigation, recommended fertilizer application amounts and timing; Scenario 4: Rain-fed, recommended fertilizer application amounts and timing. All scenarios have 3.5 and 4 month varieties with the exception of Scenario 4 that only has one growing season with a 3.5 month variety. All scenarios use conventional tilling practices. Yield, CO_2, and N leaching are rounded to the nearest thousand; CH_4 and N_2O are rounded to the nearest hundred.

4.3 Sensitivity Analysis

For the sensitivity analysis, DNDC defaults provided the range for the parameters in the Monte Carlo simulation. It is important to note the ranges used in the Monte Carlo simulation (Appendix C) when looking at the results. In particular the relatively large SOC range, 0.1 kg C/ha, should be taken into account. The SOC value is 0.0076 kg C/ha (DNDC default value based on soil type), so the large range around this number is unlikely to be seen in the field. Of the tested parameters, among the most sensitive were clay content, pH, and SOC (Appendix C). CDFs of N leaching, yield, and GHG values (N_2O, NO, NH_3, and N_2) based on these three parameters provided information on which factor was the most important determinant for the output's outcome as a B or NB value. The red lines are the B values that are greater than the set behavior value, and the blue lines are the NB values, below the set behavior value (Figures 4.3, 4.4, and 4.5).

Higher leaching rates required lower clay fraction and slightly lower SOC values, while N leaching rates were fairly constant as pH changed (Figures 4.3, 4.4, and 4.5). N leaching was most affected by the amount of clay in the paddy. Changes in yield were not affected by pH differences, and a higher yield resulted from slightly lower clay fraction in the field. SOC was the most important parameter for yield, shown by the large difference in SOC values associated with high and low yields. A low SOC value corresponded with a high yield (Appendix C).

Greater GHG emissions of N_2O, NO, NH_3, and N_2 were a result of slightly larger SOC values. Conversely a larger clay fraction reduced GHG emissions. As pH became more basic,

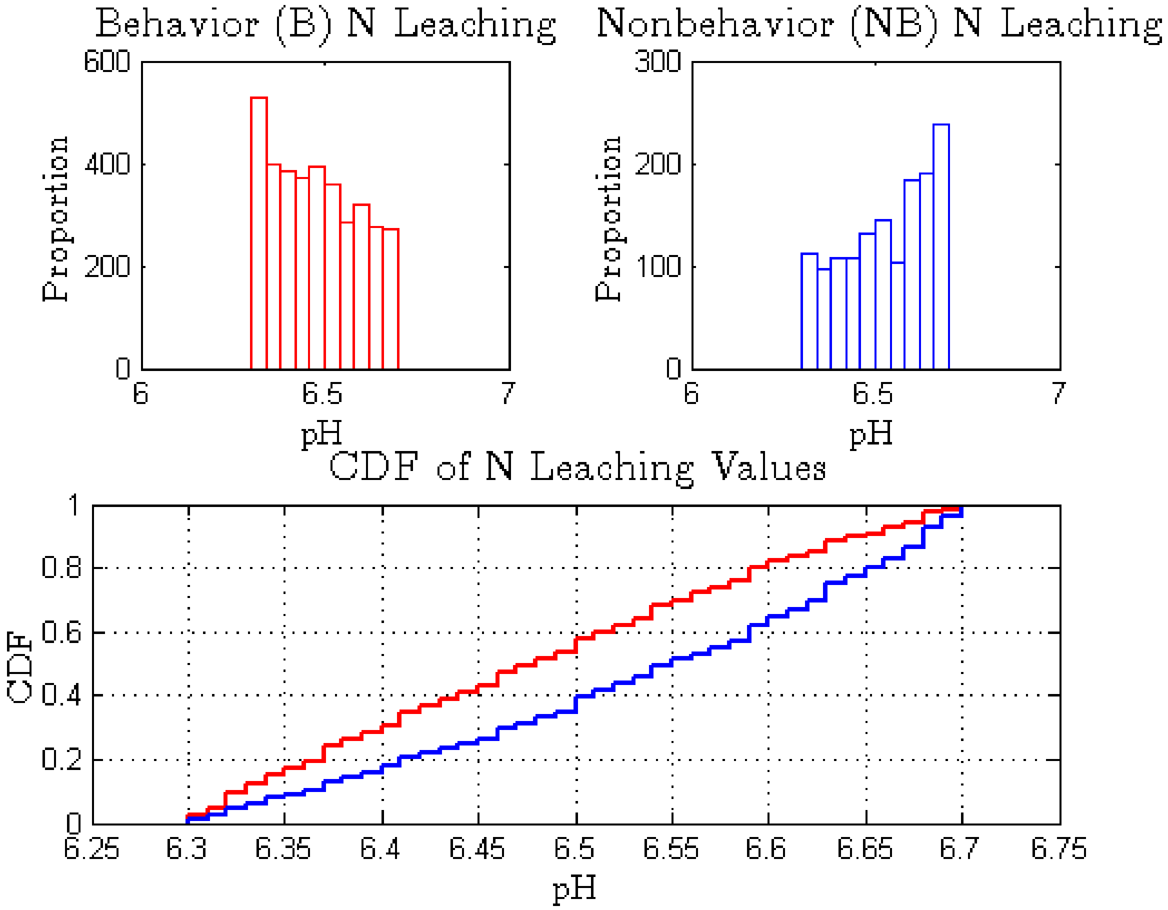


Figure 4.3: The red histogram shows the proportion of larger (B) N leaching values and the corresponding pH values; the blue histogram shows the proportion of smaller (NB) N leaching values and corresponding pH values. Below are the CDFs of both B (red) and NB (blue), N leaching values with regard to pH. N leaching results are fairly consistent for the range of pH values, with slightly higher leaching levels at a lower pH.

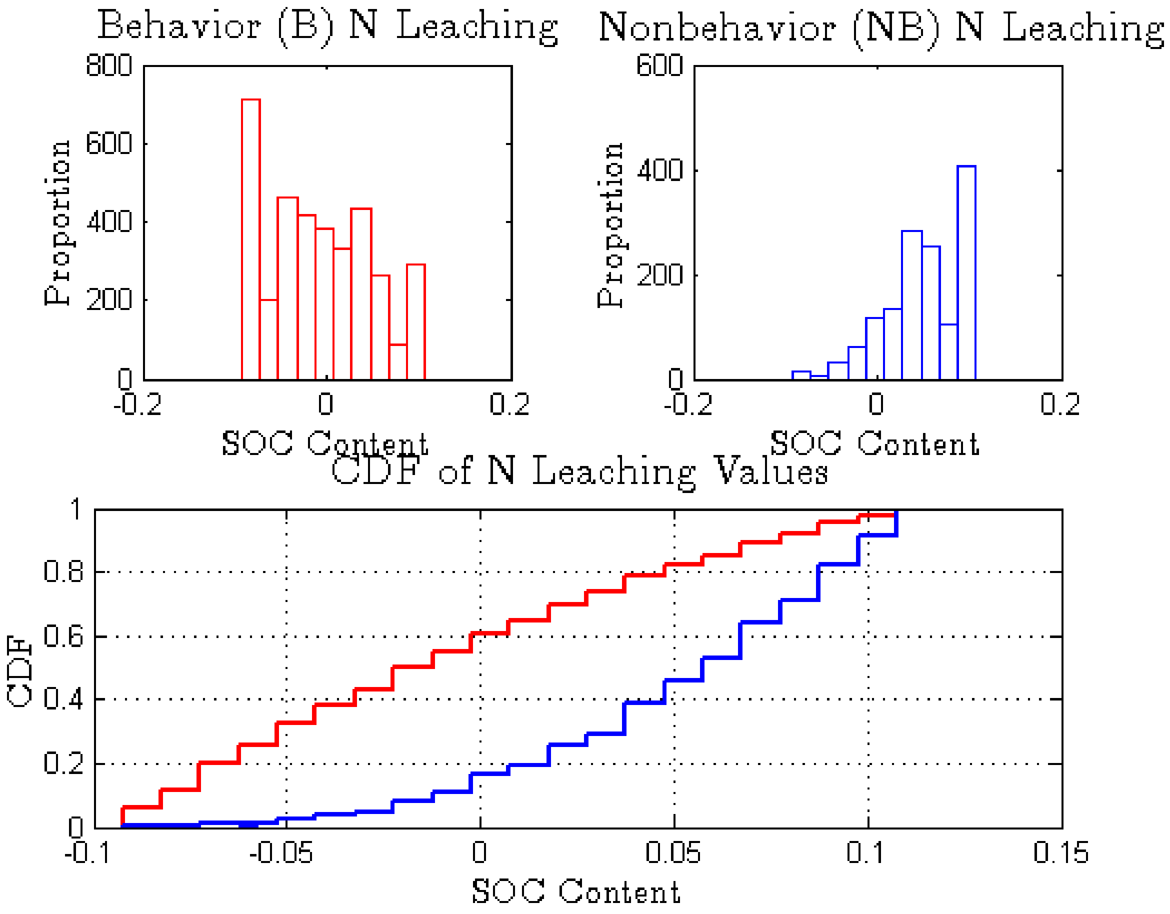


Figure 4.4: The red histogram shows the proportion of larger (B) N leaching values and the corresponding SOC values; the blue histogram shows the proportion of smaller (NB) N leaching values and corresponding SOC. Below are the CDFs of both B (red) and NB (blue), N leaching values with regard to SOC. N leaching increases with lower SOC values (NB values).

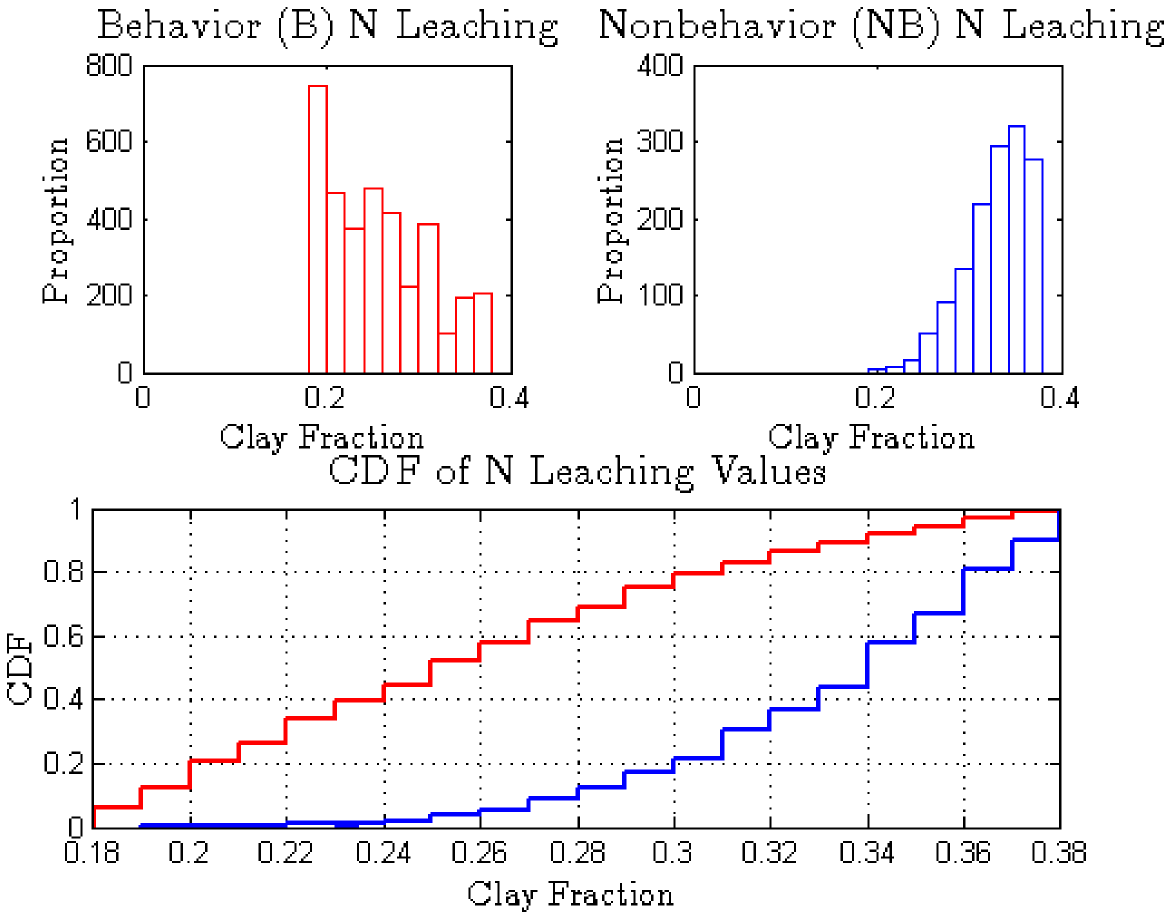


Figure 4.5: The red histogram shows the proportion of larger (B) N leaching values and the corresponding clay values; the blue histogram shows the proportion of smaller (NB) N leaching values and corresponding clay fraction. Below are the CDFs of both B (red) and NB (blue), N leaching values with regard to clay. N leaching decreases with higher clay values (B values).

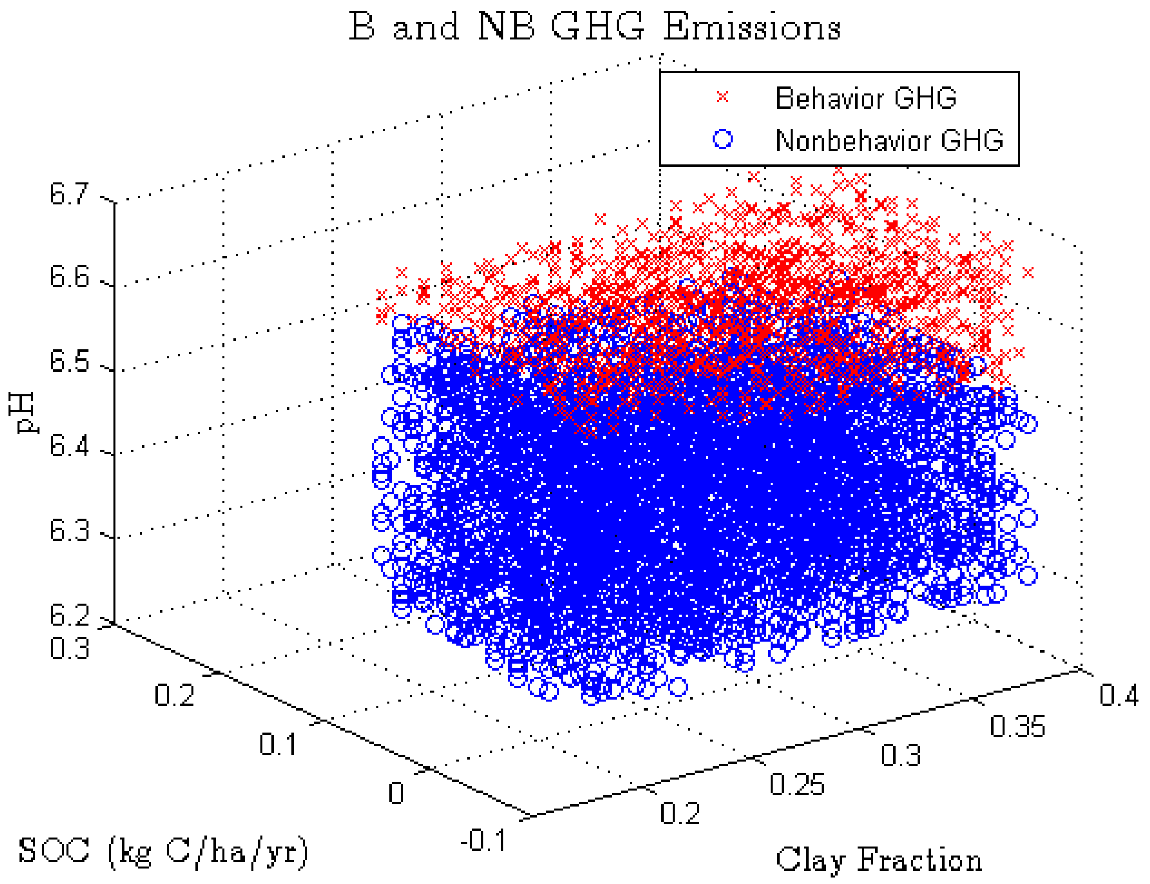


Figure 4.6: N_2O, NO, NH_3, and N_2 emissions covarying with soil parameters SOC, pH, and clay content. Blue circles are values below the behavior value, 36 kg N/ha/y, and red x's are values above the behavior value.

GHG emissions decreased (Appendix C).

A plot of the three parameters covarying for each of the outputs, and corresponding B and NB values, visualizes which parameters most affected each output (Figures 4.3, 4.4, and 4.5).

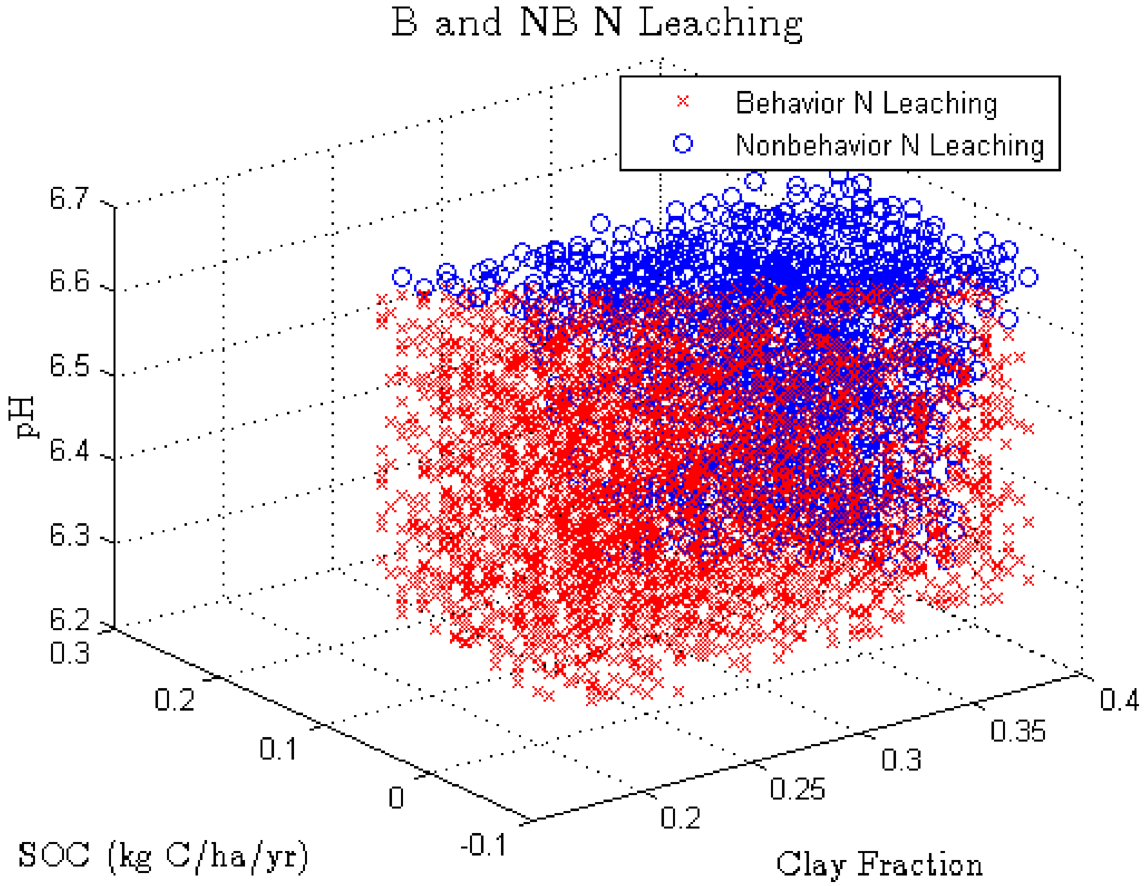


Figure 4.7: N leaching values covarying with soil parameters SOC, pH, and clay content. Blue circles are values below the behavior value, 65 kg N/ha/y, and red x's are values above the behavior value.

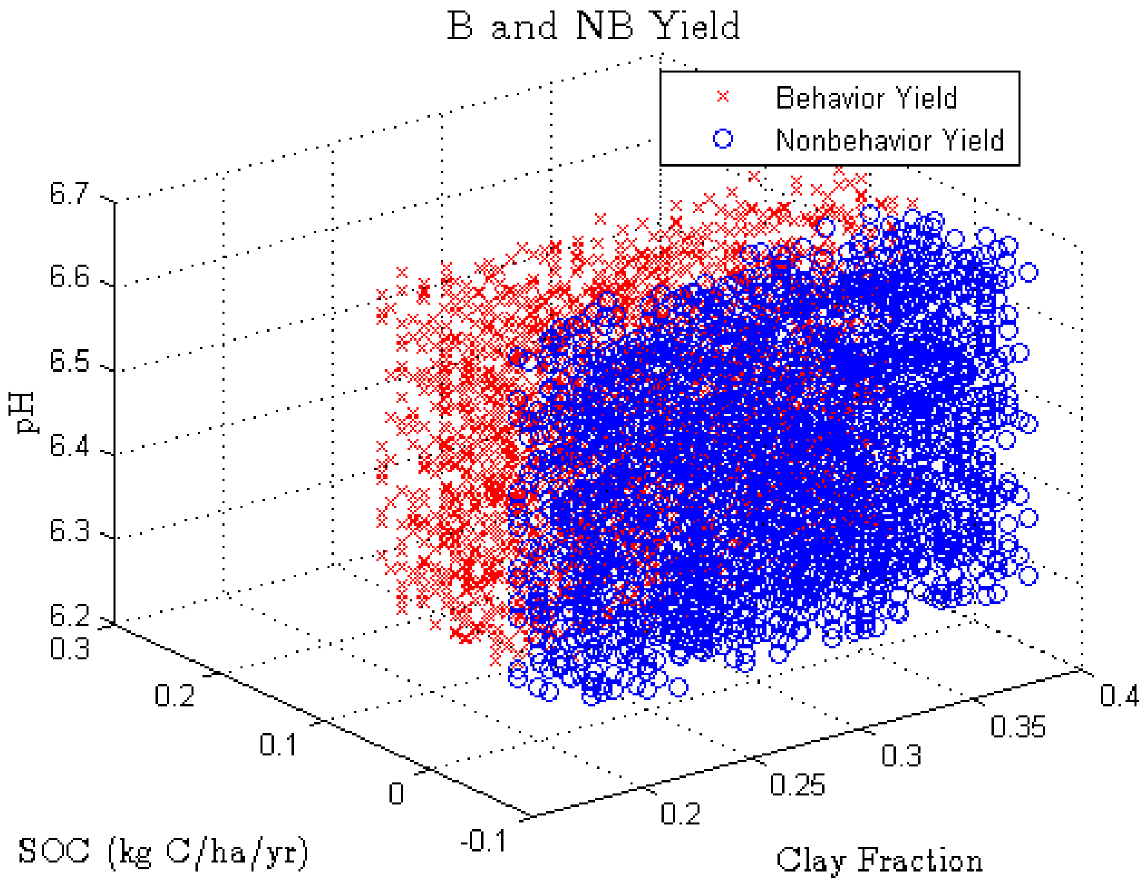


Figure 4.8: Yield values covarying with soil parameters SOC, pH, and clay content. Blue circles are values below the behavior value, 4,1000 kg C/ha/y, and red x's are values above the behavior value.

Chapter V

DISCUSSION

5.1 Environmental and Management Variability

This research used the DNDC model as a tool with which to simulate how alternate paddy management strategies in a changing Sri Lankan climate can influence rice yield, GHG emissions, and nitrate leaching in two settings. Developing countries like Sri Lanka must determine how their agricultural systems can adapt to climate change while continuing to grow, and regional analyses like this can assist decision makers on all levels. Farmers, agricultural extension agents, and government planners can use these results and the DNDC model to better plan cropping calendars, irrigation schedules, and fertilizer practices for specific environmental settings, while considering the impact of rice cultivation on the environment.

While there is little variability in N leaching, yield, and GHG emissions for Aralaganwila and Maha Illuppallama, gradients in soil, precipitation, and temperature across the agroecological zones may have a larger impact on these outputs. In both irrigated and rain-fed systems, the biggest concern is N leaching into freshwater resources as a result of the overapplication of fertilizer. Increases in fertilizer application negatively impacted groundwater resources, as N leaching values increased proportionally with fertilizer inputs, but notably the additions did not improve yield in either setting. Superfluous fertilization also greatly increased CH_4 emissions. Based on these results, there are minimal trade-offs of rice yield or environmental impacts associated with lower fertilizer amounts. Agricultural officials in Sri Lanka should encourage changes in fertilizer application rates in irrigated systems as well as rain-fed. They could demonstrate, using field methods or this model, that following the Department of Agriculture's recommended fertilizer schedule (Appendix B) compared to superfluous fertilization results in the same rice yield. They could also encourage applying clay to the base and edges of their fields to prevent losses of nitrogen through seepage and percolation with water resources (*Sivapalan and Palmer*, 2014).

As conventional tilling and no-till management had minimal differences in outputs, encouraging farmers in rain-fed systems across Sri Lanka to improve tilling methods would reduce the country's yield by 5% and have no impact on N leaching while barely reducing GHG emissions. No-till management can increase SOC, but based on these results it would not be beneficial for a farmer to use these techniques if he was looking to maximize yield (*Pittelkow et al.*, 2014). Therefore it would not be productive to encourage changes in farmers' tilling practices.

Across the country, farmers are most limited by access to water. As a frequent coping mechanism in response to drought, farmers in rain-fed systems abandon cultivation in the dry season, *yala*. Access to a reliable irrigation network can prevent this loss. Officials in rain-fed systems could consider storing rain-fall and setting up irrigation systems, particularly as water from the monsoons becomes less reliable. Control over rain-fed systems can decrease N leaching, and provide confidence that water will reach fields during both growing seasons.

Sri Lankan farmers would need to consider this especially if access to water becomes a pressing concern. If drought was an issue in irrigated systems as well, reducing the depth of irrigation and frequency by such practices as AWD could help maintain yield but would double N leaching as compared to traditionally irrigated system. If the agriculture sector of the country shifted to AWD techniques due to water scarcity, the quantity of available freshwater would increase but the quality could decline, so large-scale water testing would need to be in place.

Should the entire country shift to large-scale irrigation, CO_2 emissions would have a tenfold increase, contributing to global GHG concentrations. While this is a cause for concern, Sri Lanka is a small nation about the size of West Virginia. Practicing AWD and increasing the pH of paddy soil by adding limestone could reduce CO_2 emissions without affecting yield.

5.2 Broader Impacts

Agrarian communities depend heavily on agricultural productivity for subsistence farming as well as livelihood, tying them closely to environmental changes. Sri Lanka is dependent on the South Asia monsoon for rainfall, which is strongly related to ENSO events (*Zubair*, 2002, 2005; *Kane*, 1998). The monsoon schedule has shifted onset dates and intensities (*Jacobi*, 2014). Precipitation has declined in recent decades and climate scenarios predict that rainfall will continue to decrease while evaporation increases (*De Silva et al.*, 2007). Over the past 50 years, Sri Lanka has already seen an increase in temperature of 1°C (*Zubair*, 2005).

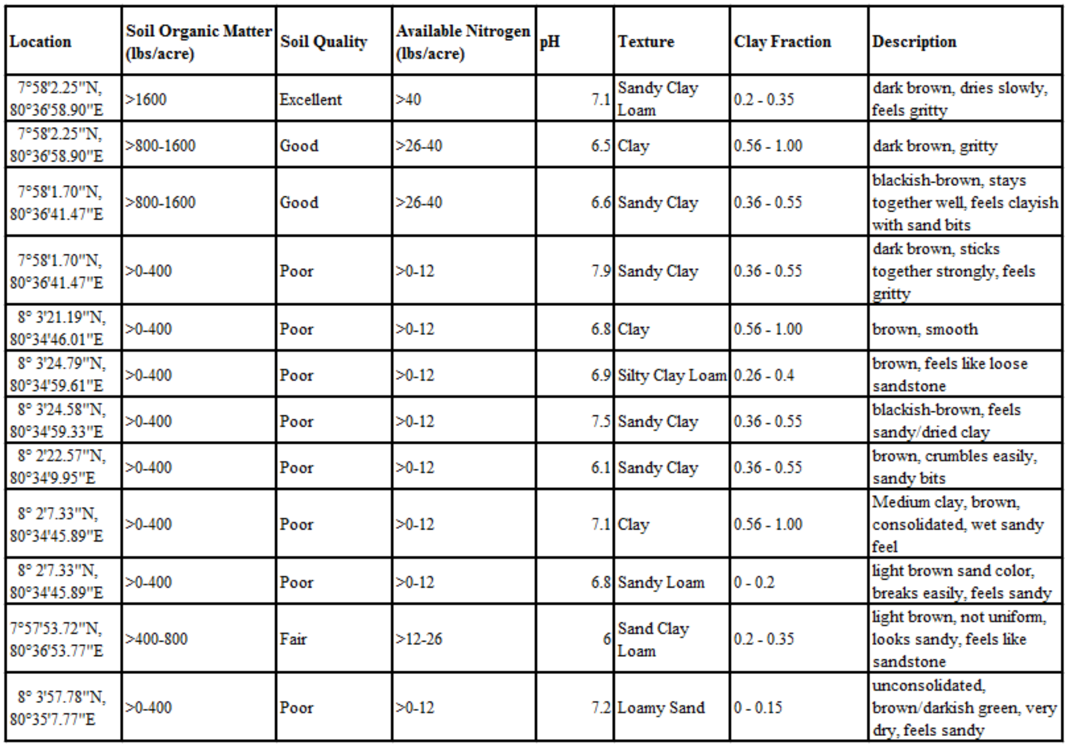
In order to develop socially acceptable, economically feasible, and environmentally sustainable rice-based agricultural systems, rice production must adopt new technologies and management approaches. New strategies for water saving include AWD, direct seeding, short duration and drought-resistant seeds, transplanting, plant spacing, better soil and nutrient management, and mulching and green manure (*Talpur et al.*, 2011). Informed decisions on irrigation schedules can help lead to optimal yield and environmental impact. There are opportunities for further fertilizer efficiency through improved crop and soil management. Evaluations of the current fertilizer subsidy, credit programs for farmers, and agricultural insurance systems could lead to constructive changes for farmers' agricultural outcomes and impact on the environment.

For a small country like Sri Lanka, the primary concern for paddy cultivation should be controlling water quality and the effects of N leaching, not minimizing GHG emissions. Global anthropogenic sources of N, primarily due to additions from the manufacture of fertilizer, are twice that of natural sources (*Rockström et al.*, 2009). Identifying opportunities for N efficiency through improved crop and soil management can prevent disruptions to natural N pathways and in particular N losses through leaching into freshwater resources. The World Health Organization sets the maximum contaminant level goal (MCLG), or the level of contaminants in drinking water at which no adverse health effects are likely to occur, at 10 mg/L or pmm. N leaching has serious implications for drainage water quality, including groundwater toxicity and health concerns for drinking water. N runoff is a separate output to be considered because this N in surface water leaving the field accumulates in water resources for drinking, cleaning, and irrigation. Elevated nitrate levels in drinking water can cause respiratory infection and lead to thyroid metabolism modifications; great amounts of N-nitroso compounds are known carcinogens. Nitrate in groundwater also causes methemoglobinemia (blue baby syndrome) in infants (*Kendall et al.*, 2007; *Follett and Hatfield*, 2001). Studies show that excess nitrate leaching may be associated with chronic kidney disease of unknown etiology (CKDue) in Sri Lanka, of concern particularly in the dry zone where there is a high prevalence of CKDue (*Wanigasuriya et al.*, 2007; *Chandrajith et al.*, 2009).

As rainfall patterns change, temperature increases, and the population grows, Sri Lanka and its agricultural community must be prepared to adapt to a changing climate. Climate change will affect Asian agrarian sectors more than most countries due to the strong reliance on water and agriculture in the region. These countries are especially vulnerable to climate change events due to an already stressed marginal environment, frequent exposure to catastrophic events, and lack of capital for adaptation or mitigation measures (*Fischer et al.*, 2005). Effective water management is particularly important in countries that are reliant on agriculture and freshwater resources will be even more precious in the changing climate.

Appendix A

SOIL DATA



Location	Soil Organic Matter (lbs/acre)	Soil Quality	Available Nitrogen (lbs/acre)	pH	Texture	Clay Fraction	Description
7°58'2.25"N, 80°36'58.90"E	>1600	Excellent	>40	7.1	Sandy Clay Loam	0.2 - 0.35	dark brown, dries slowly, feels gritty
7°58'2.25"N, 80°36'58.90"E	>800-1600	Good	>26-40	6.5	Clay	0.56 - 1.00	dark brown, gritty
7°58'1.70"N, 80°36'41.47"E	>800-1600	Good	>26-40	6.6	Sandy Clay	0.36 - 0.55	blackish-brown, stays together well, feels clayish with sand bits
7°58'1.70"N, 80°36'41.47"E	>0-400	Poor	>0-12	7.9	Sandy Clay	0.36 - 0.55	dark brown, sticks together strongly, feels gritty
8° 3'21.19"N, 80°34'46.01"E	>0-400	Poor	>0-12	6.8	Clay	0.56 - 1.00	brown, smooth
8° 3'24.79"N, 80°34'59.61"E	>0-400	Poor	>0-12	6.9	Silty Clay Loam	0.26 - 0.4	brown, feels like loose sandstone
8° 3'24.58"N, 80°34'59.33"E	>0-400	Poor	>0-12	7.5	Sandy Clay	0.36 - 0.55	blackish-brown, feels sandy/dried clay
8° 2'22.57"N, 80°34'9.95"E	>0-400	Poor	>0-12	6.1	Sandy Clay	0.36 - 0.55	brown, crumbles easily, sandy bits
8° 2'7.33"N, 80°34'45.89"E	>0-400	Poor	>0-12	7.1	Clay	0.56 - 1.00	Medium clay, brown, consolidated, wet sandy feel
8° 2'7.33"N, 80°34'45.89"E	>0-400	Poor	>0-12	6.8	Sandy Loam	0 - 0.2	light brown sand color, breaks easily, feels sandy
7°57'53.72"N, 80°36'53.77"E	>400-800	Fair	>12-26	6	Sand Clay Loam	0.2 - 0.35	light brown, not uniform, looks sandy, feels like sandstone
8° 3'57.78"N, 80°35'7.77"E	>0-400	Poor	>0-12	7.2	Loamy Sand	0 - 0.15	unconsolidated, brown/darkish green, very dry, feels sandy

Figure 1.1: Soil data from North Central Province, Sri Lanka. May 2013.

Appendix B

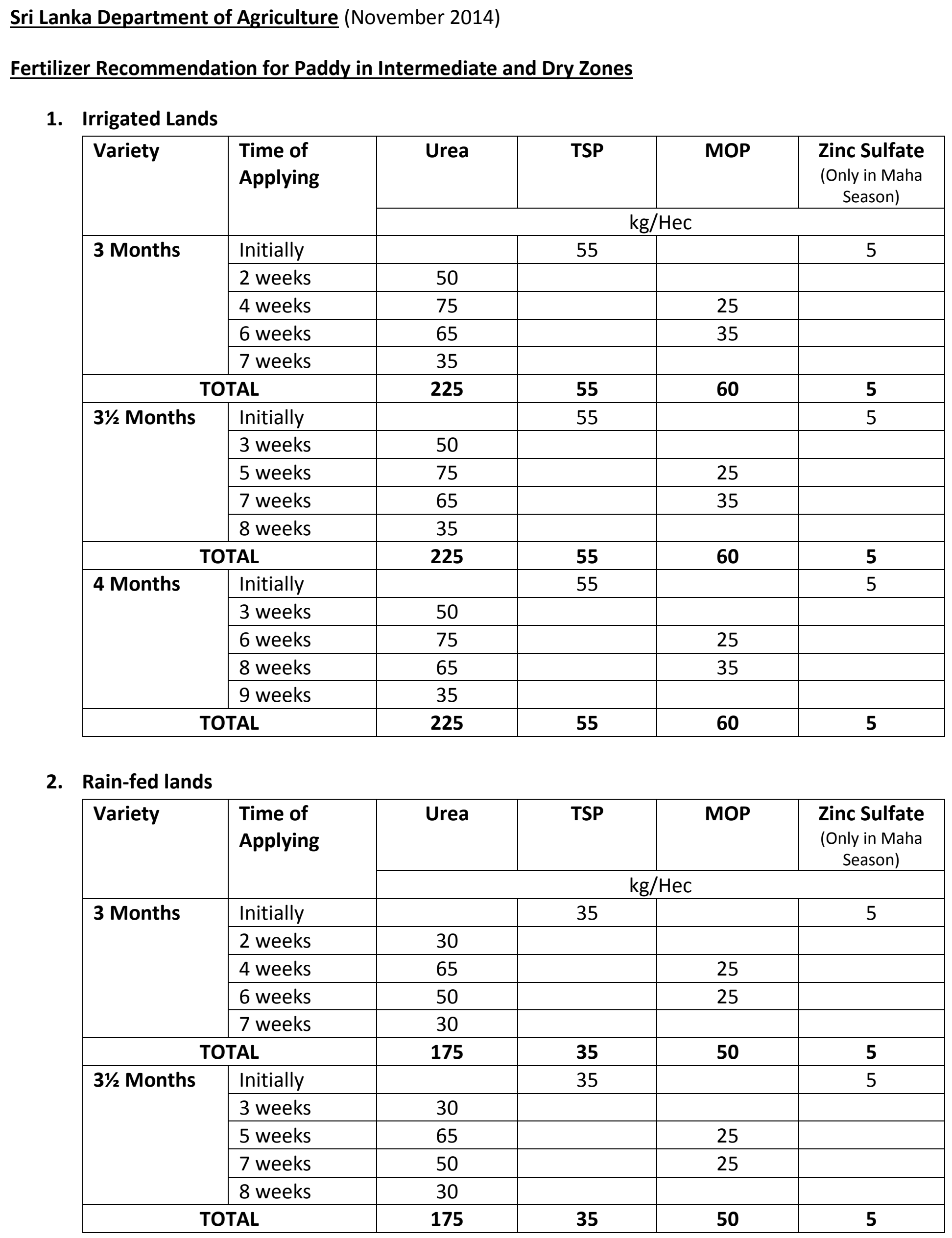
MANAGEMENT INPUTS AND RESULTS

Management Options and Outputs for Aralaganwila: Irrigated		
yield (kgC/ha/y) N leaching (kgN/ha/y)	**Recommended Fertilizer**	**Actual Fertilizer**
Conventional Tilling	160,000 1,000	180,000 2,000
No-Till	160,000 1,000	x

Table B.1 Management options and resultant DNDC outputs for an irrigated system in Aralaganwila. The yields are rounded to the nearest ten thousand, the N leaching values are rounded to the nearest thousand.

Management Options and Outputs for Maha Ilupalama: Irrigated		
yield (kgC/ha/y) N leaching (kgN/ha/y)	**Recommended Fertilizer**	**Actual Fertilizer**
Conventional Tilling	180,000 0	180,000 2,000
No-Till	180,000 0	x

Table B.2 Management options and resultant DNDC outputs for an irrigated system in Maha Illuppallama. The yields are rounded to the nearest ten thousand, the N leaching values are rounded to the nearest thousand.



Sri Lanka Department of Agriculture (November 2014)

Fertilizer Recommendation for Paddy in Intermediate and Dry Zones

1. **Irrigated Lands**

Variety	Time of Applying	Urea	TSP	MOP	Zinc Sulfate (Only in Maha Season)
		kg/Hec			
3 Months	Initially		55		5
	2 weeks	50			
	4 weeks	75		25	
	6 weeks	65		35	
	7 weeks	35			
TOTAL		**225**	**55**	**60**	**5**
3½ Months	Initially		55		5
	3 weeks	50			
	5 weeks	75		25	
	7 weeks	65		35	
	8 weeks	35			
TOTAL		**225**	**55**	**60**	**5**
4 Months	Initially		55		5
	3 weeks	50			
	6 weeks	75		25	
	8 weeks	65		35	
	9 weeks	35			
TOTAL		**225**	**55**	**60**	**5**

2. **Rain-fed lands**

Variety	Time of Applying	Urea	TSP	MOP	Zinc Sulfate (Only in Maha Season)
		kg/Hec			
3 Months	Initially		35		5
	2 weeks	30			
	4 weeks	65		25	
	6 weeks	50		25	
	7 weeks	30			
TOTAL		**175**	**35**	**50**	**5**
3½ Months	Initially		35		5
	3 weeks	30			
	5 weeks	65		25	
	7 weeks	50		25	
	8 weeks	30			
TOTAL		**175**	**35**	**50**	**5**

Figure 2.1: Fertilizer schedules from the Department of Agriculture, Sri Lanka. November, 2014.

Appendix C

SENSITIVITY ANALYSIS

Parameter	**Initial Value**	**Monte Carlo Range**	**Comment**
Clay content	0.28	0.1	Clay fraction of soil by weight for a sandy clay loam
SOC	0.0076	0.1	Total SOC including litter residue, microbes, humads, & humus from 0-5 cm
pH	6.5	0.2	

Table C.1 Monte Carlo parameters and their respective ranges.

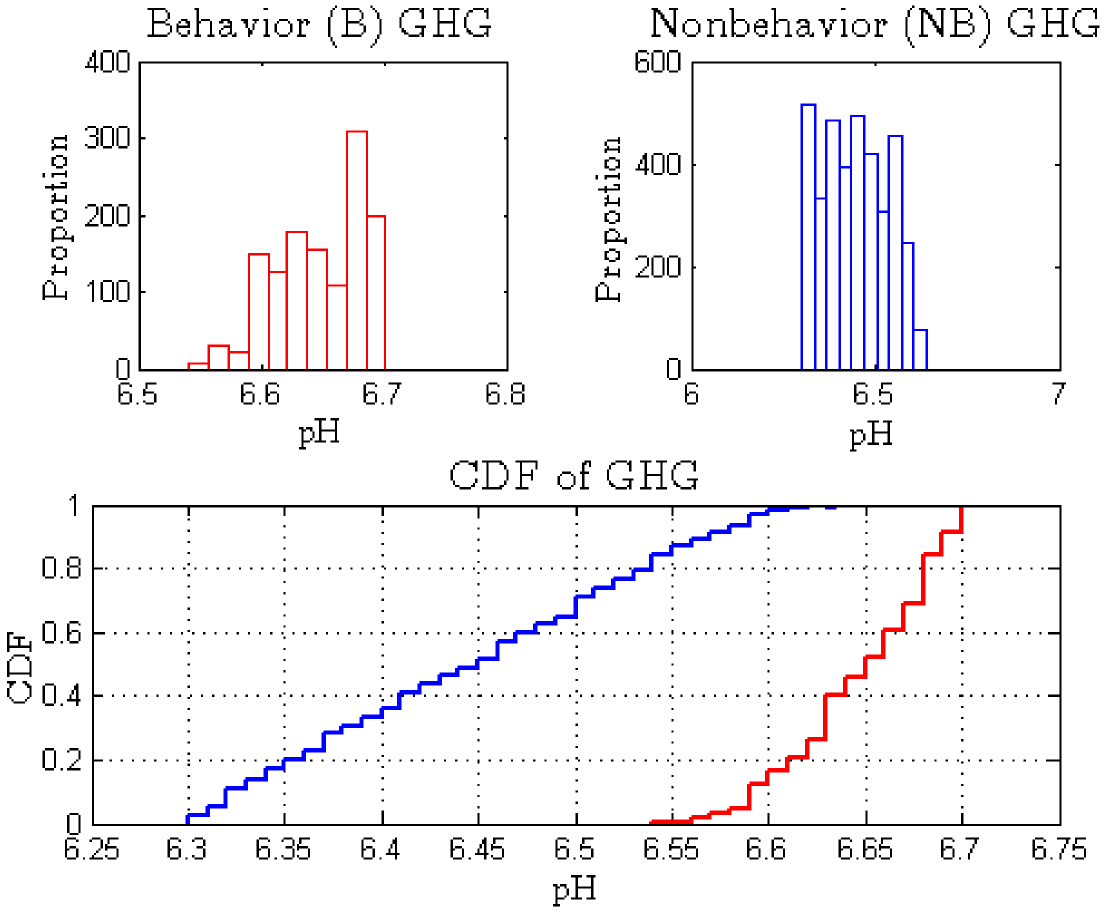


Figure 3.1: CDF of N_2O, NO, NH_3, and N_2 values with regard to pH.

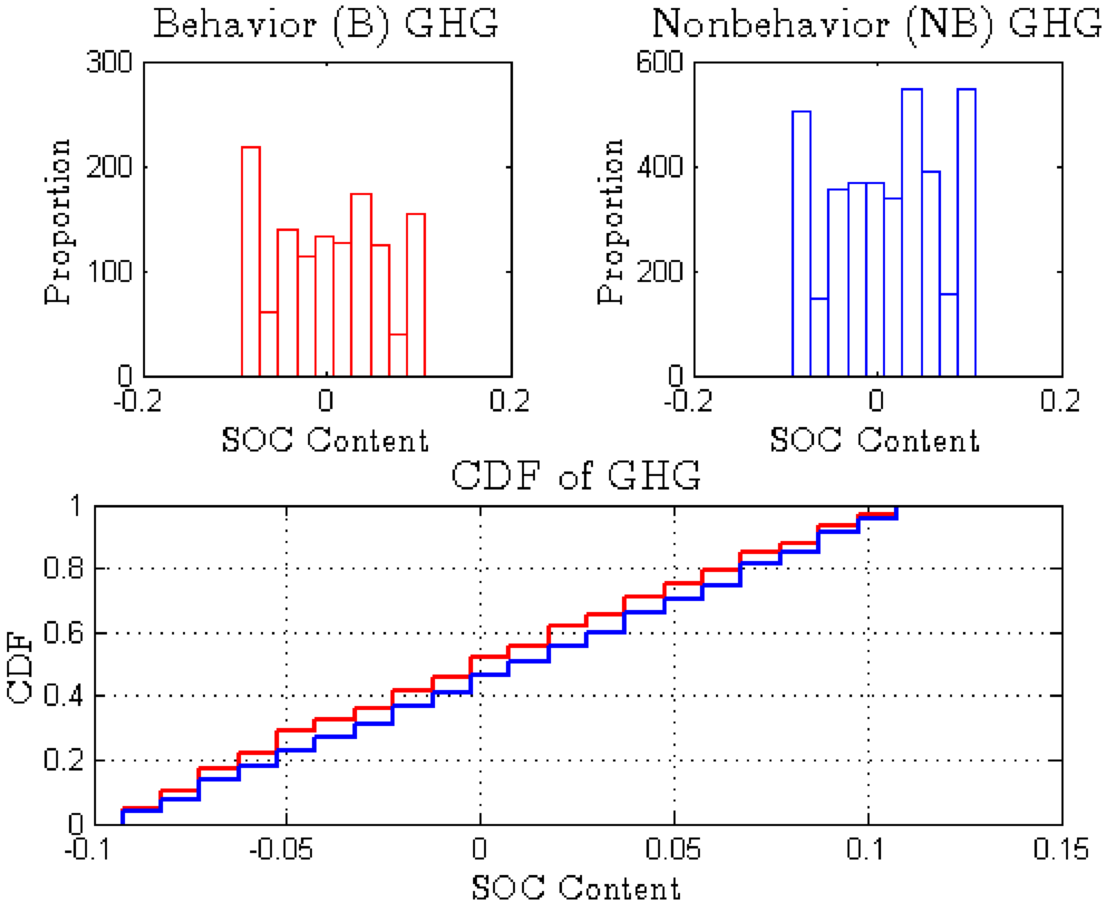


Figure 3.2: CDF of N_2O, NO, NH_3, and N_2 values with regard to SOC.

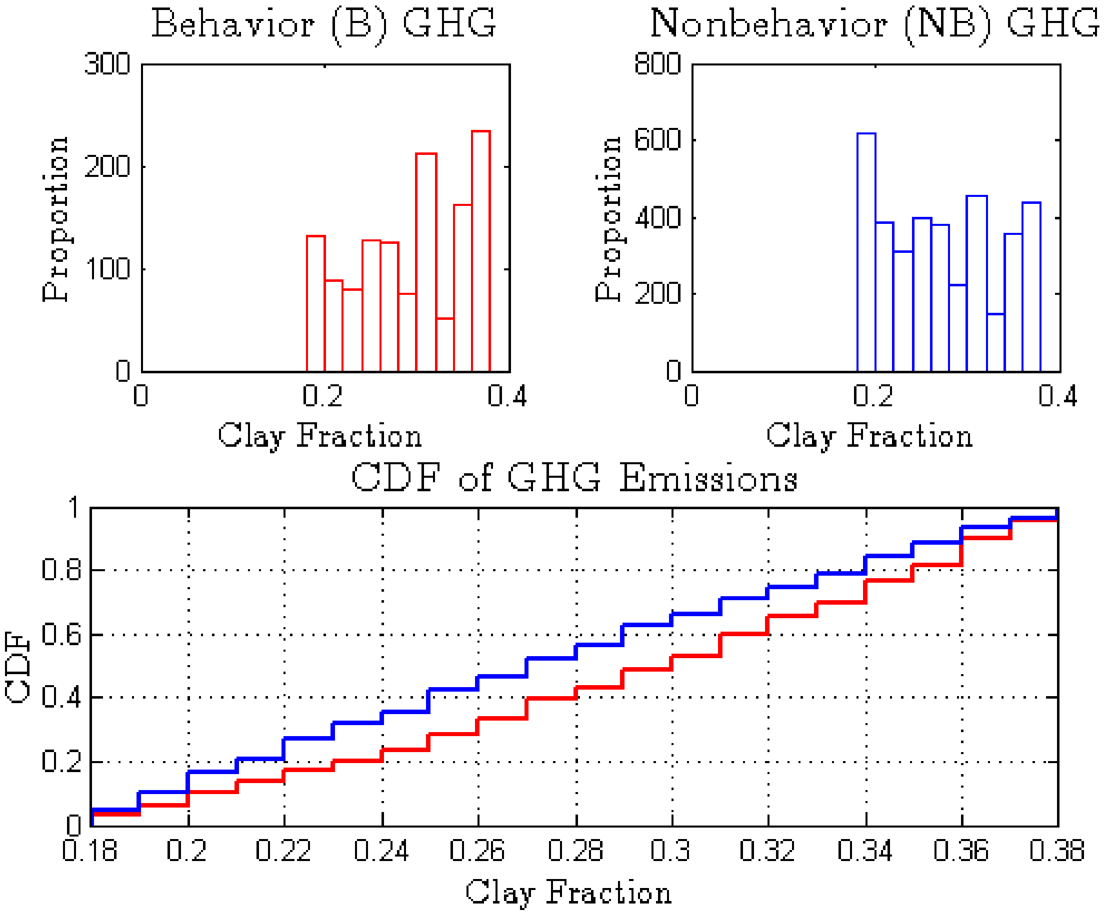


Figure 3.3: CDF of N_2O, NO, NH_3, and N_2 values with regard to clay.

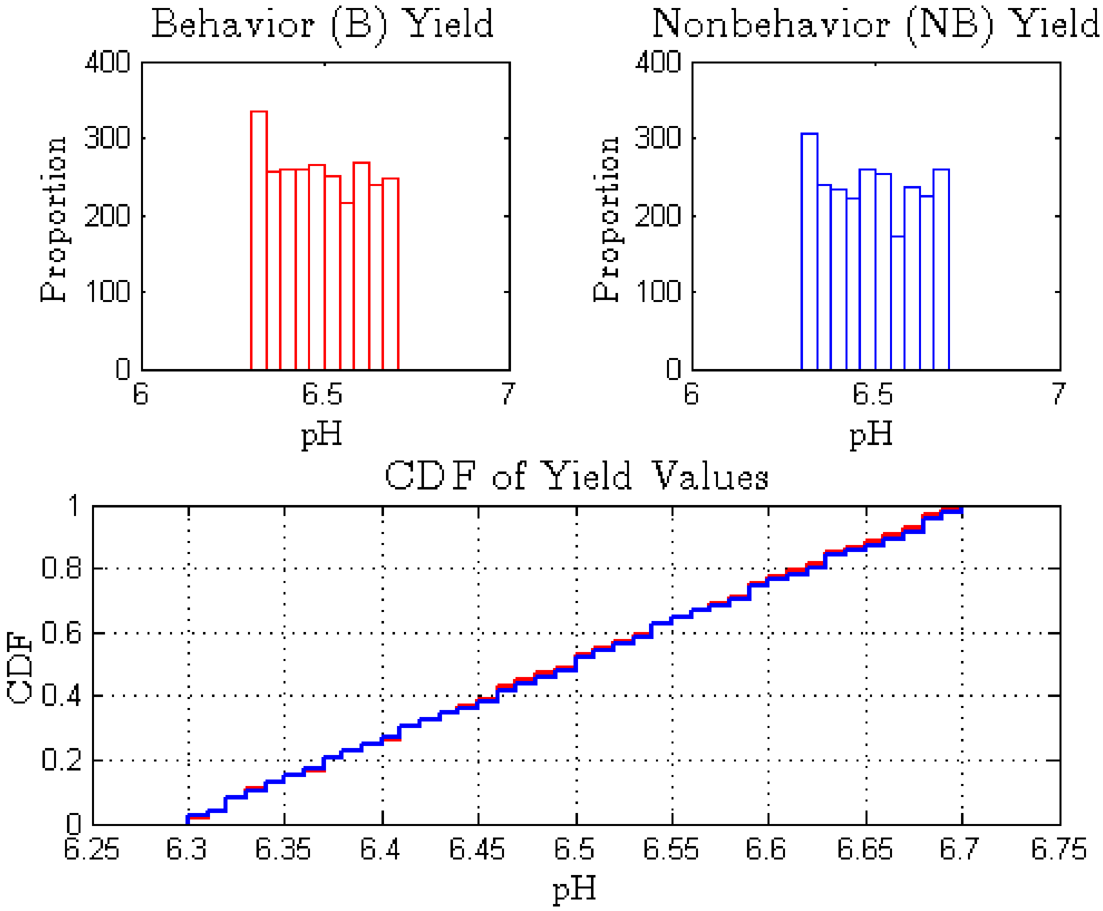


Figure 3.4: CDF of yield values with regard to pH.

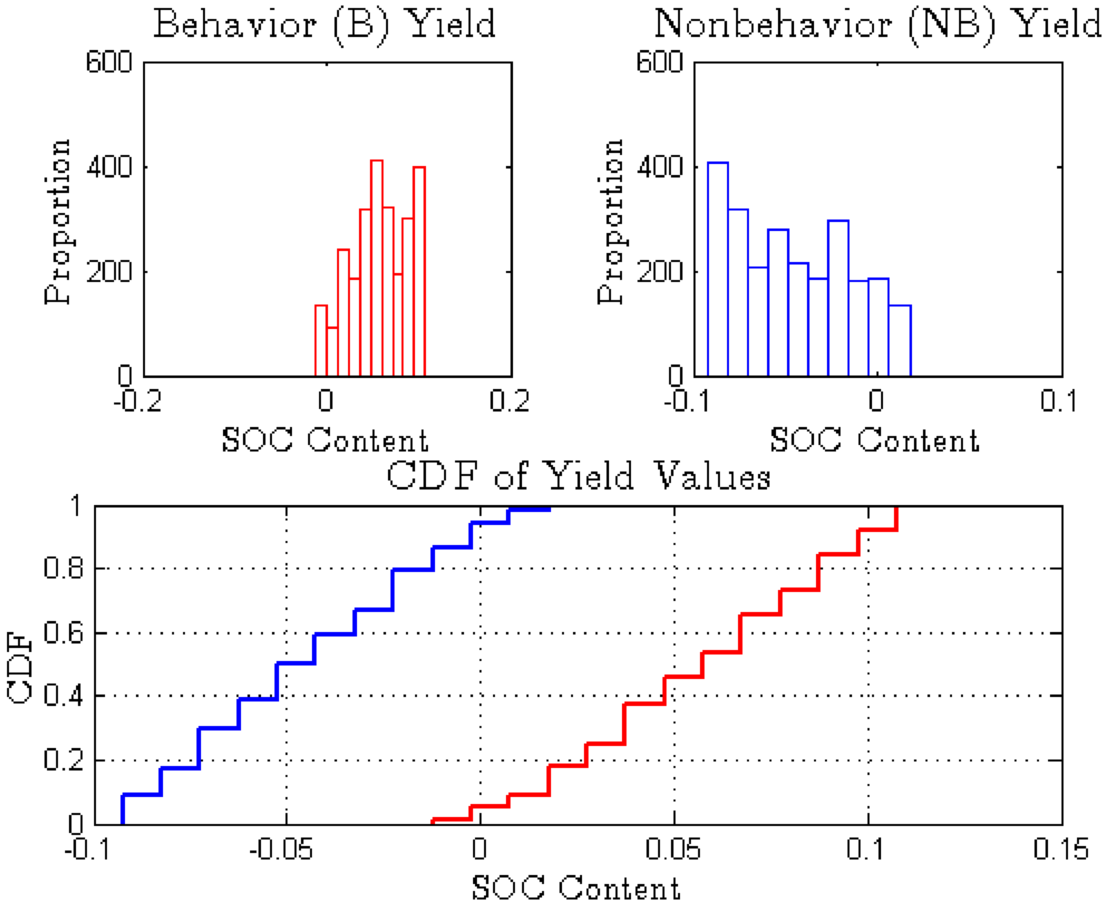


Figure 3.5: CDF of yield values with regard to SOC.

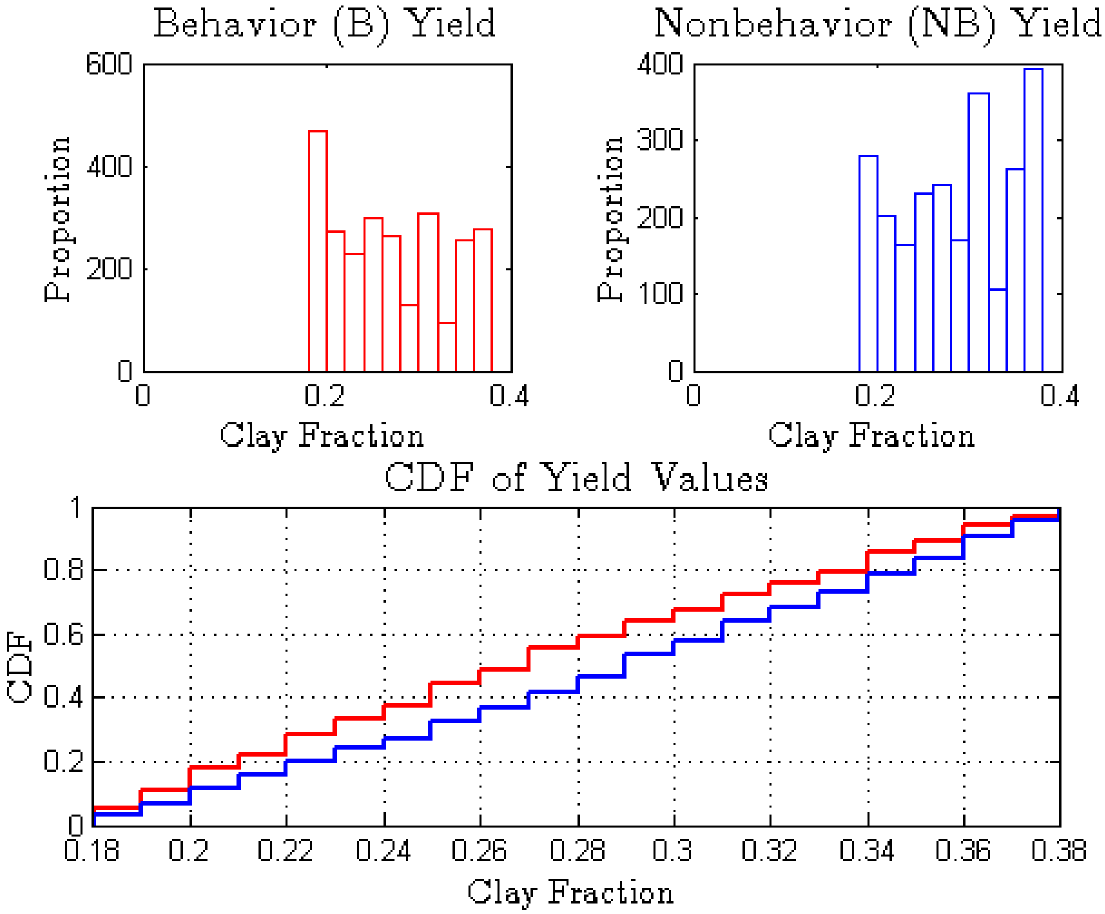


Figure 3.6: CDF of yield values with regard to clay.

References

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